

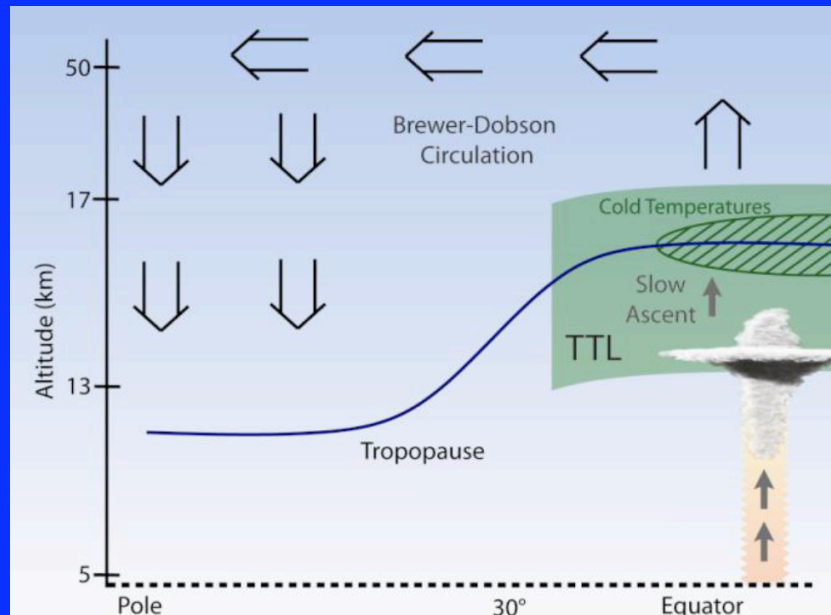
Towards an improved understanding of the Tropopause Transition Layer

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Early morning preparations to study deep convection in the Tropical Chemistry, Clouds and
Climate Coupling (TC4) Field Experiment, July 2007

The Tropical Tropopause Transition Layer (TTL) is a region of mixed tropospheric and stratospheric properties around the tropical tropopause



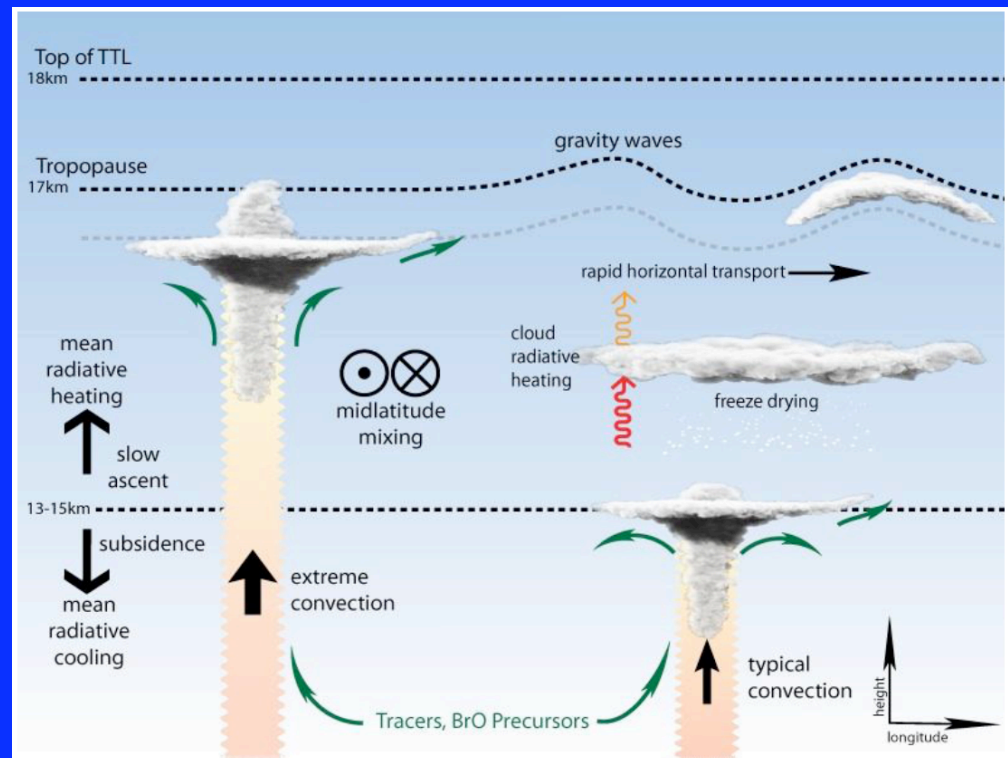
A range of dynamical, chemical, and microphysical processes affect the TTL and stratospheric composition.

TTL

Height: ~12km to 16 or 17 km

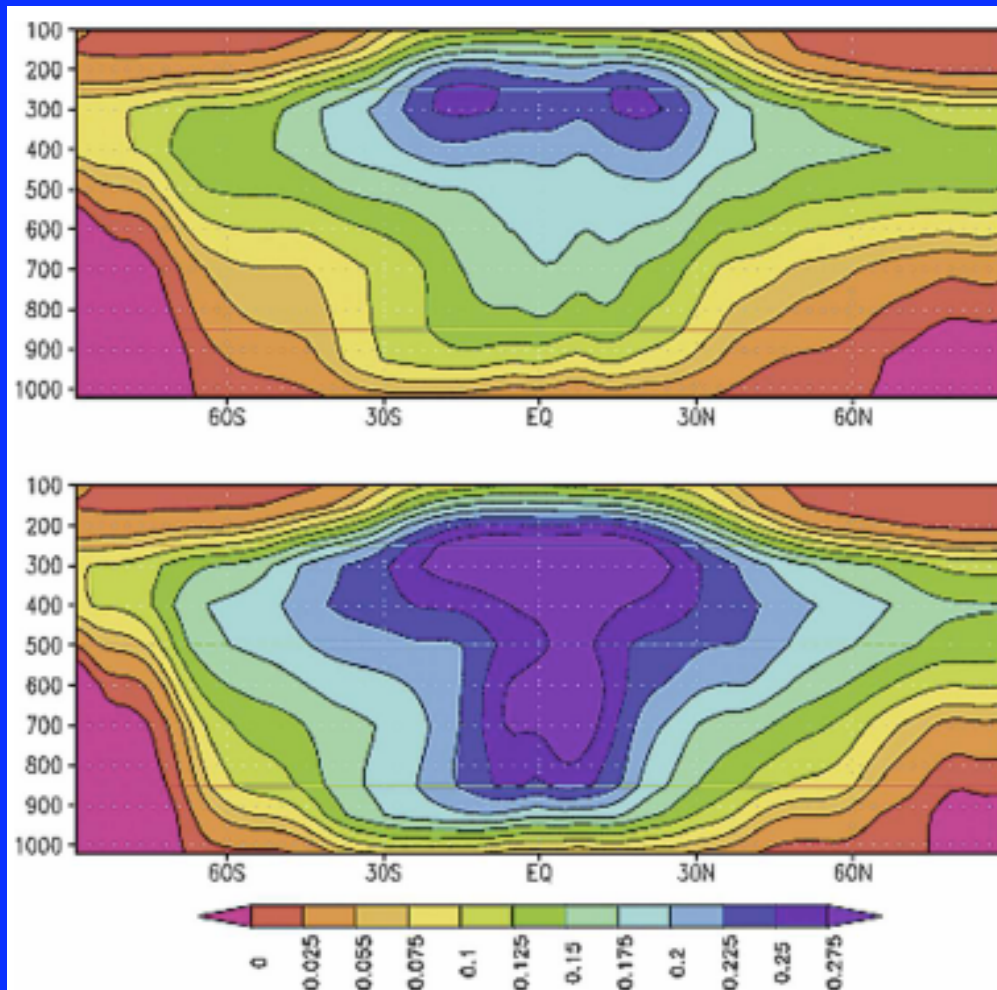
Pressure: 200 hPa to 100 or 90 hPa

Θ : 350K to 380K



Why care about the TTL?

1) radiative forcing by water vapor



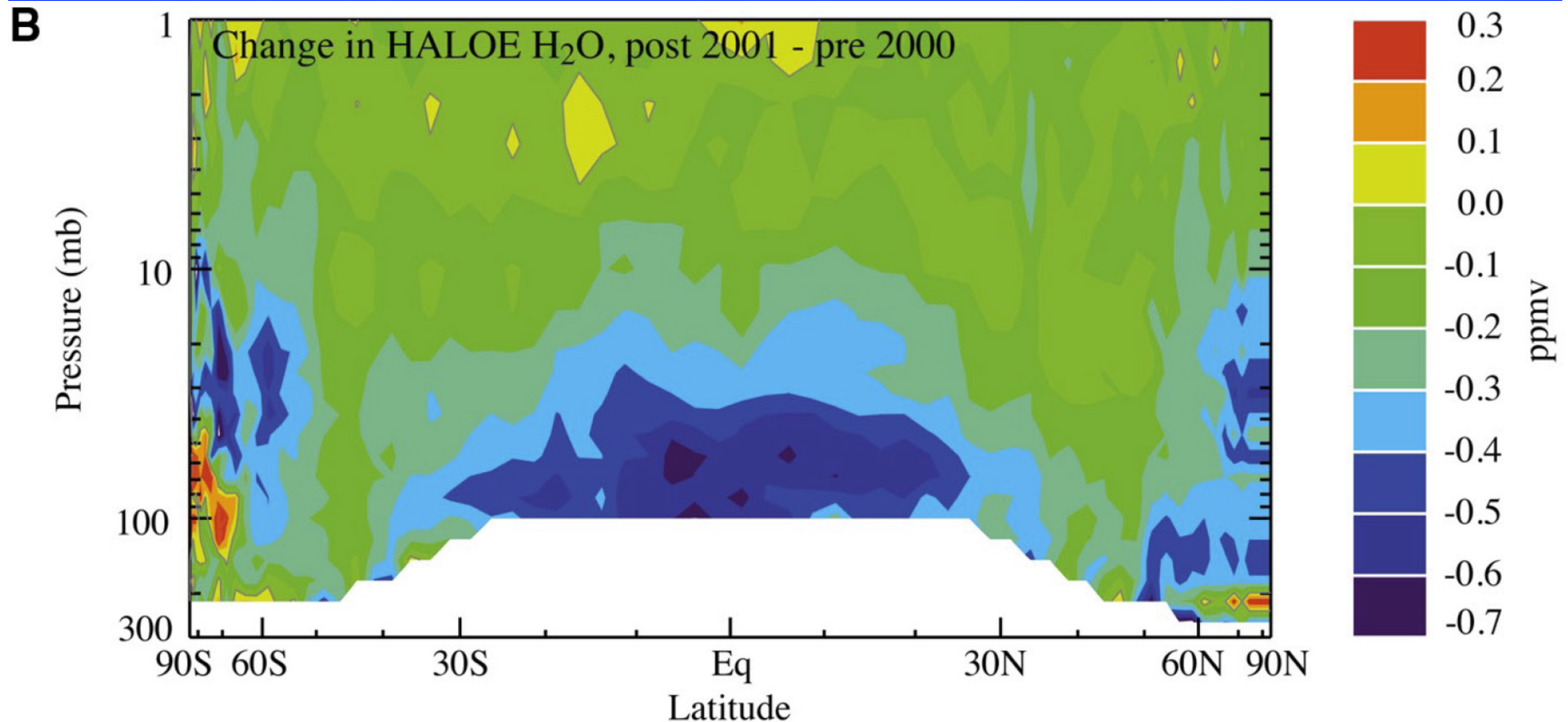
The surface radiative forcing due to water vapor equivalent to a 1K temperature change and constant relative humidity. All sky-top, clear-bottom Soden et al., J. Climate, 21, 3504, 2008.

humidity for a 1-K temperature increase), a pressure average of K^w yields the total effect of the column temperature perturbation on the TOA longwave flux

Small changes in stratospheric humidity have been shown to have impacts on radiative forcing and climate comparable to increasing greenhouse gases [Solomon et al., *Science*, 2010].

2001-2005 H₂O vs 1996-2000 H₂O: -0.098 W/m^2

1996-2005 CO₂ increase: $+0.26 \text{ W/m}^2$

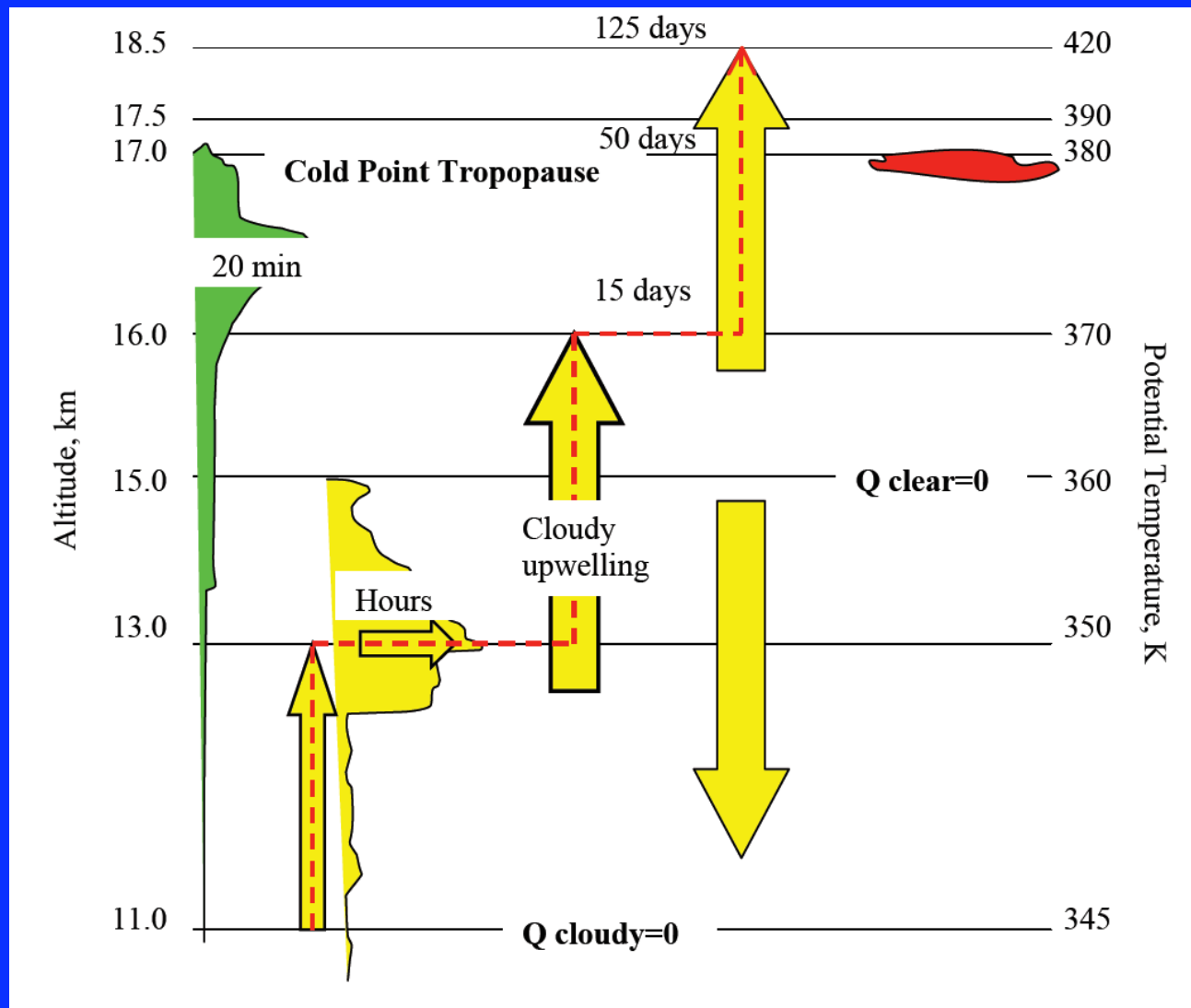


There are multiple theories about how the moisture in the TTL is determined

Direct
injection

Anvil
radiative
forcing

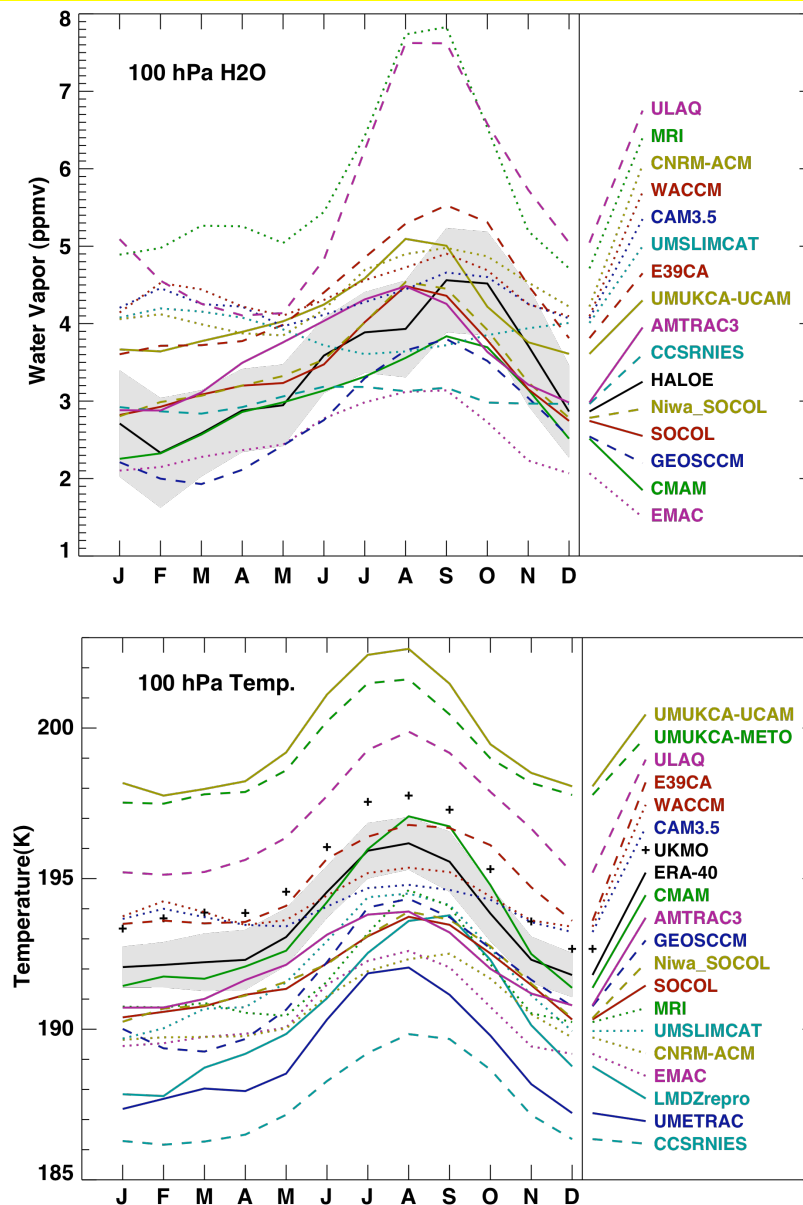
Cirrus
and SVC
radiative
forcing



air mass flux
 $\sim 10^{10}$ kg/s

air mass flux
from boundary
layer
 $\sim 1-2 \times 10^{11}$ kg/s

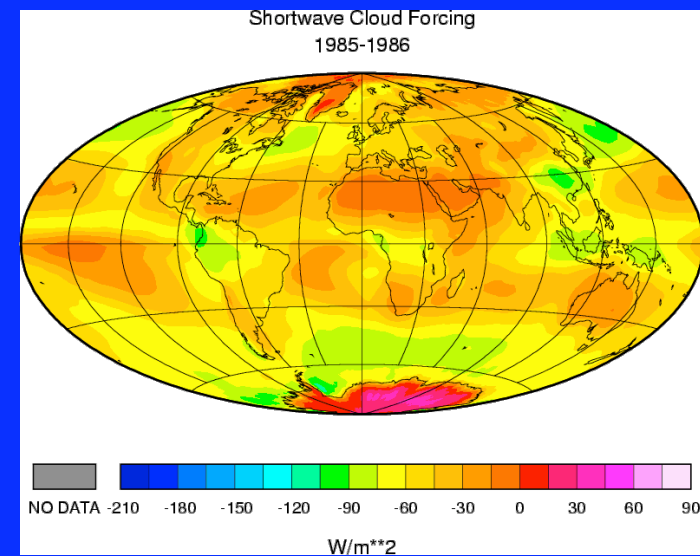
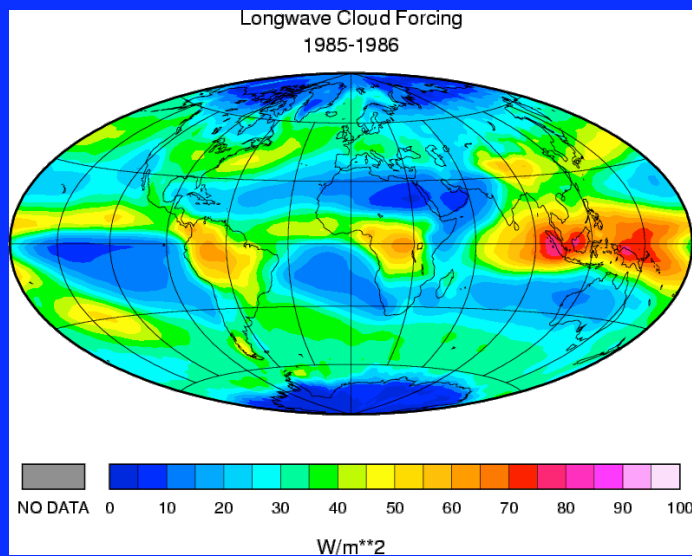
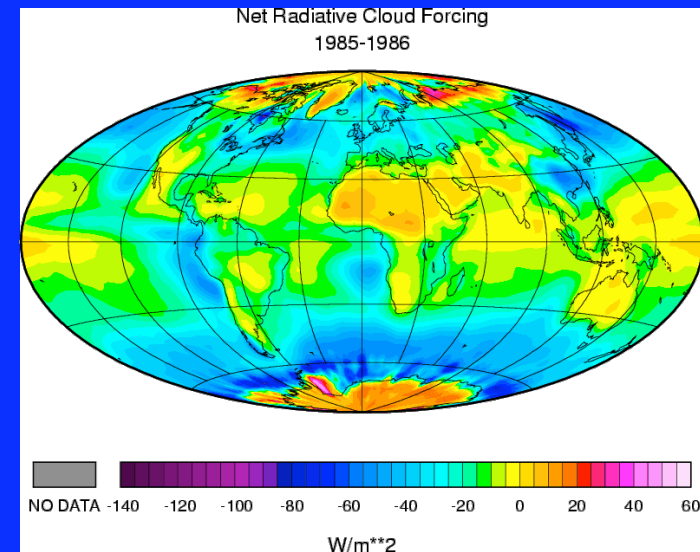
Tropical tropopause temperature and stratospheric humidity are poorly represented in global models.



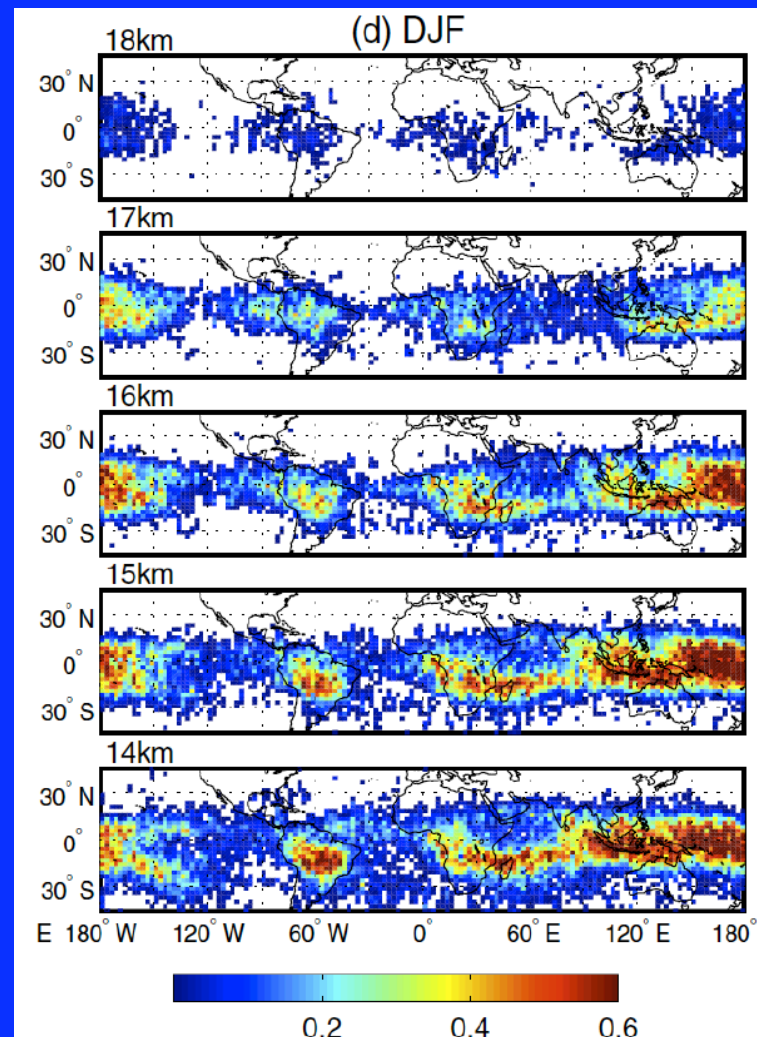
Gettleman et al., 2009

Why care about the TTL?

2) cloud radiative and transport properties



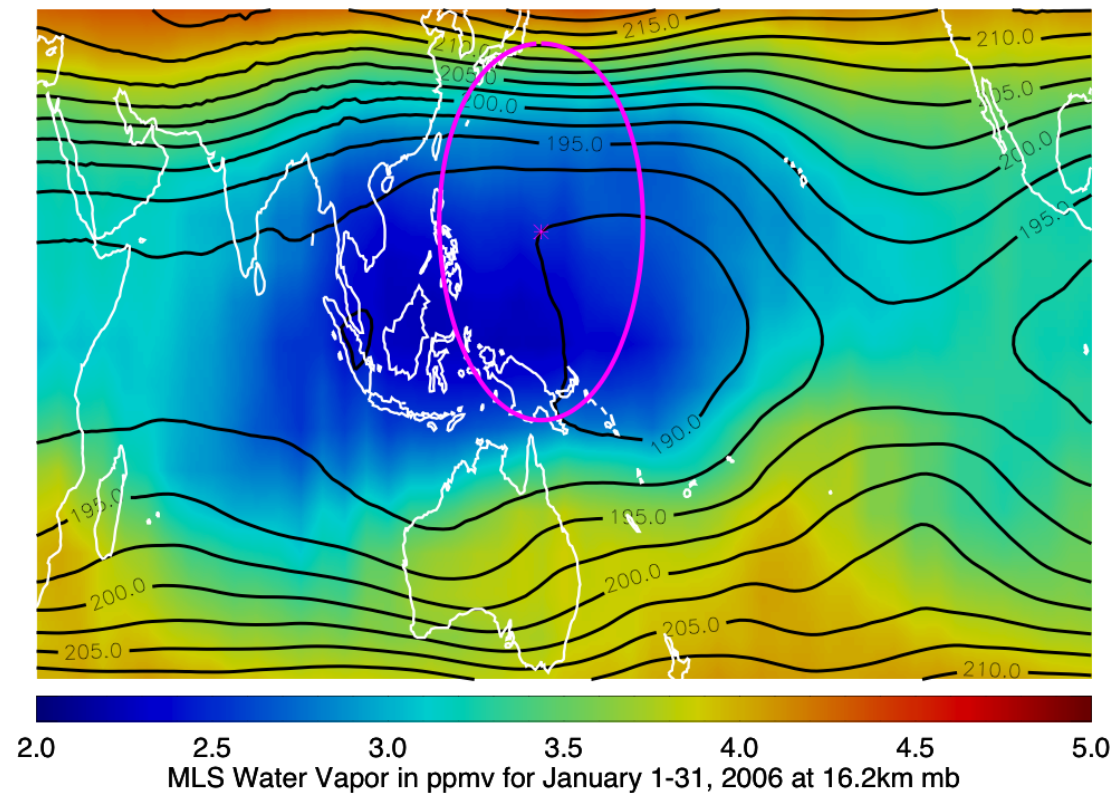
Thin cirrus that occur with very high frequency in the TTL are important for the radiation budget and humidity of the stratosphere.



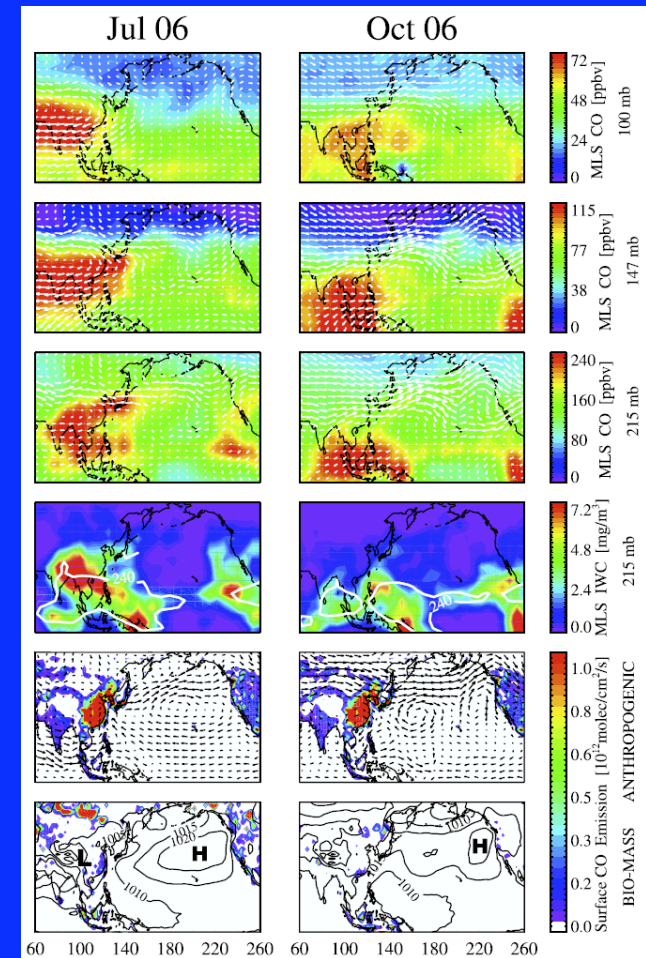
Yang et al., 2009

Why care about the TTL?

3) transport of short-lived species to the stratosphere



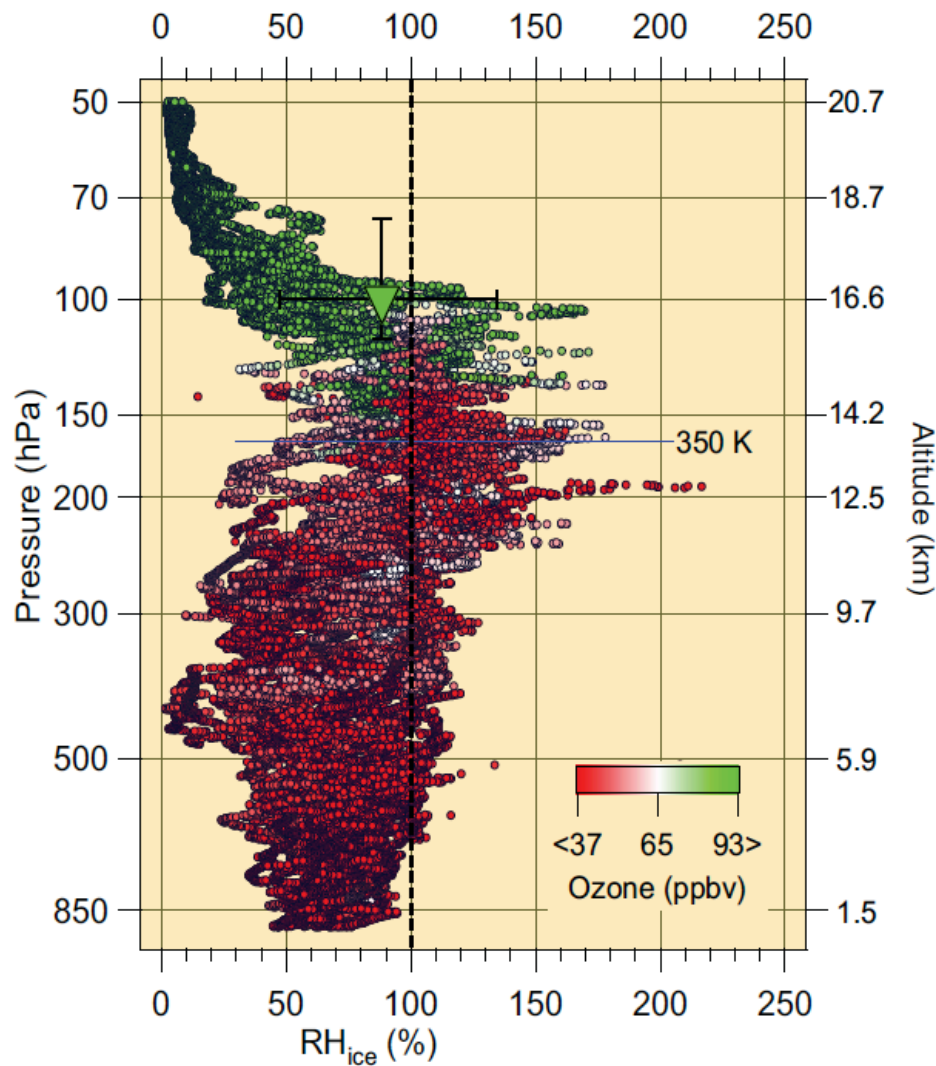
Dry air seems to enter the stratosphere over Indonesia



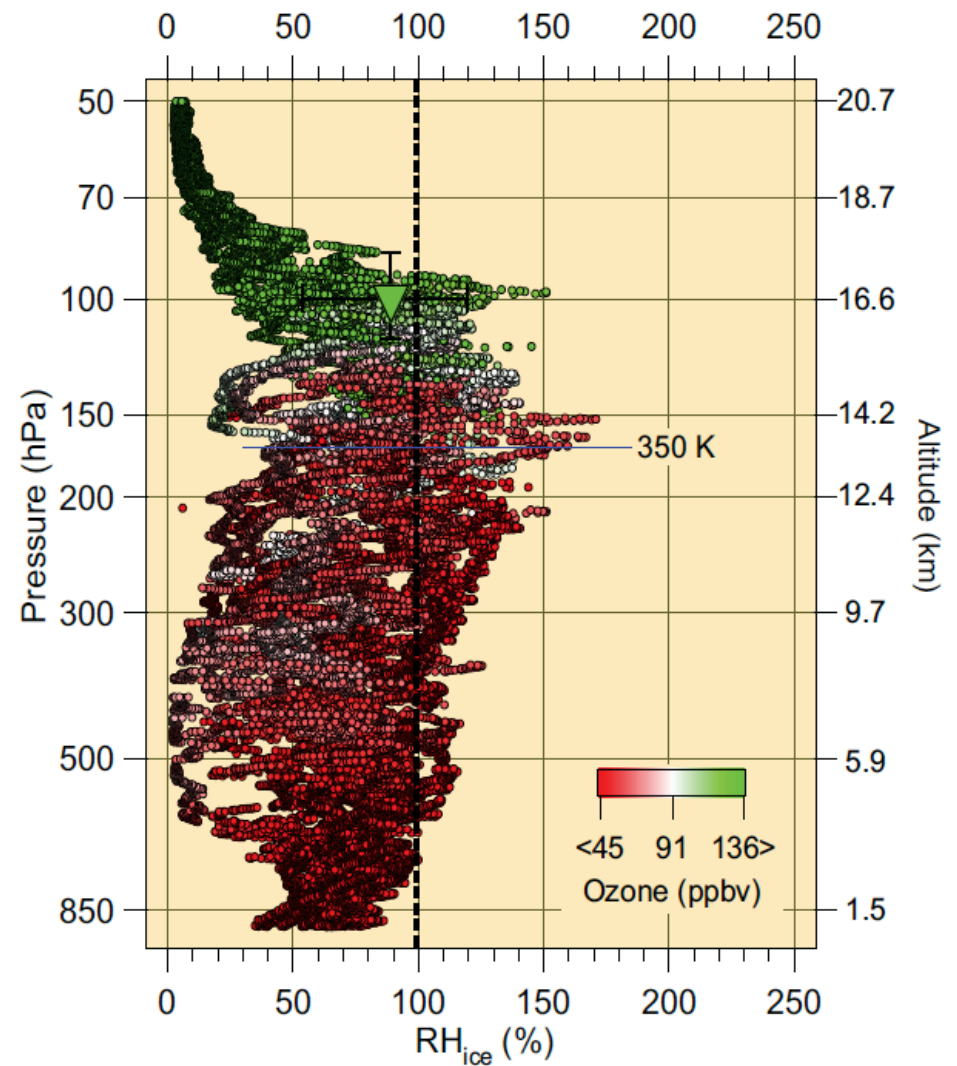
Air pollution from Asia is entering the stratosphere in Asian monsoon anticyclone

Sonde data shows frequent supersaturation over Costa Rica

Selkirk et al. 2010



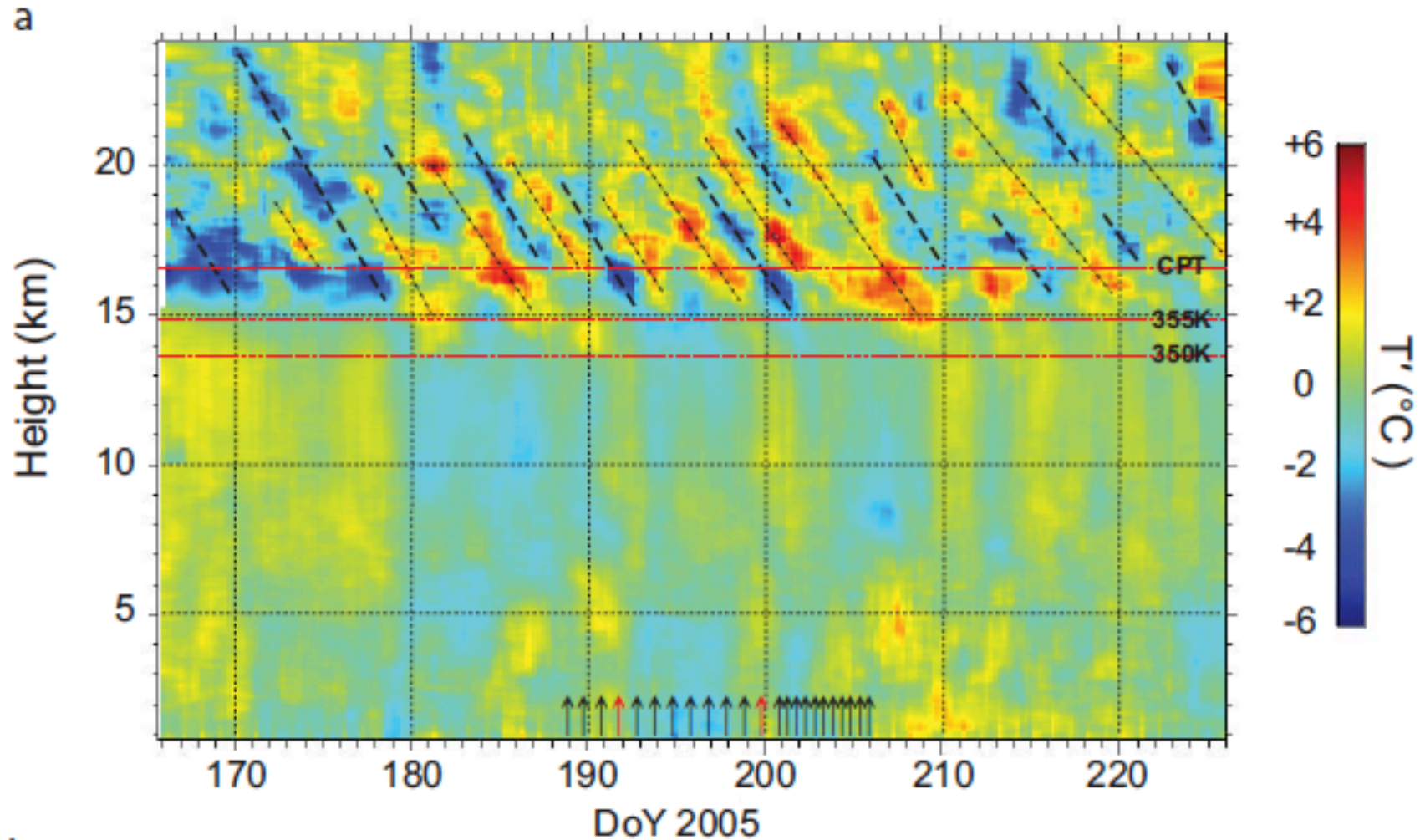
TCSP



TC4

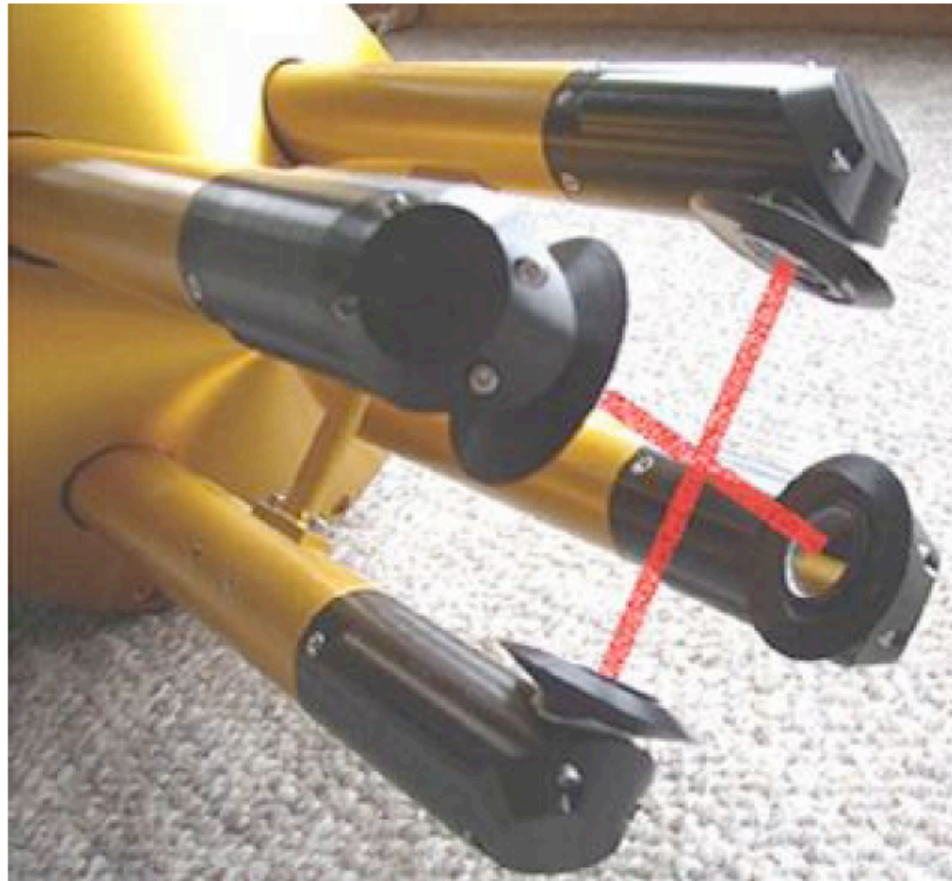
Temperature anomalies above 15 km are driven by equatorial waves

Selkirk et al. 2010

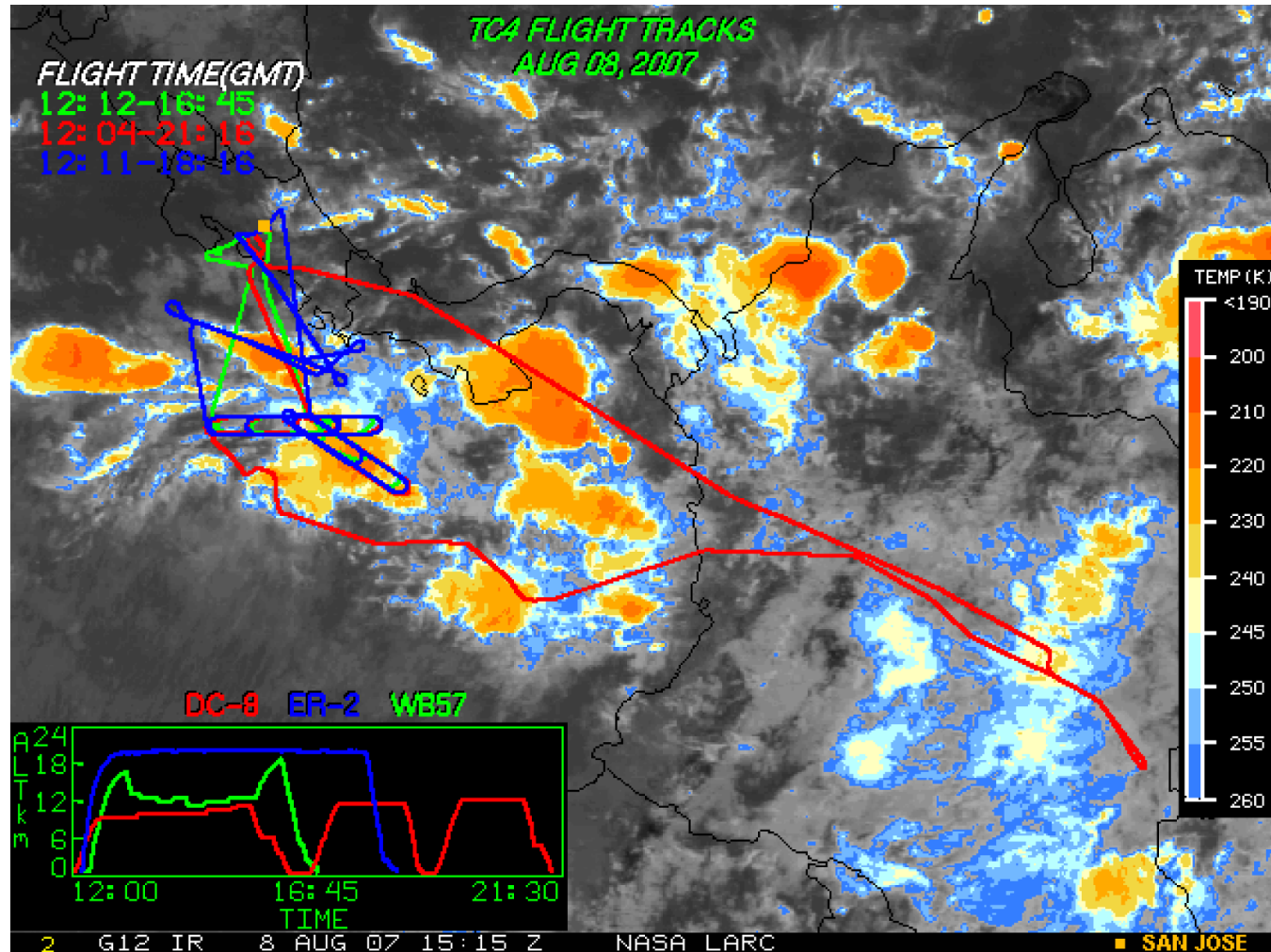


Cloud particle sizing instruments may bias data by shattering. 2D-S instrument minimizes shattering and detects artifacts

Jensen et al., ACPD 5321, 2009

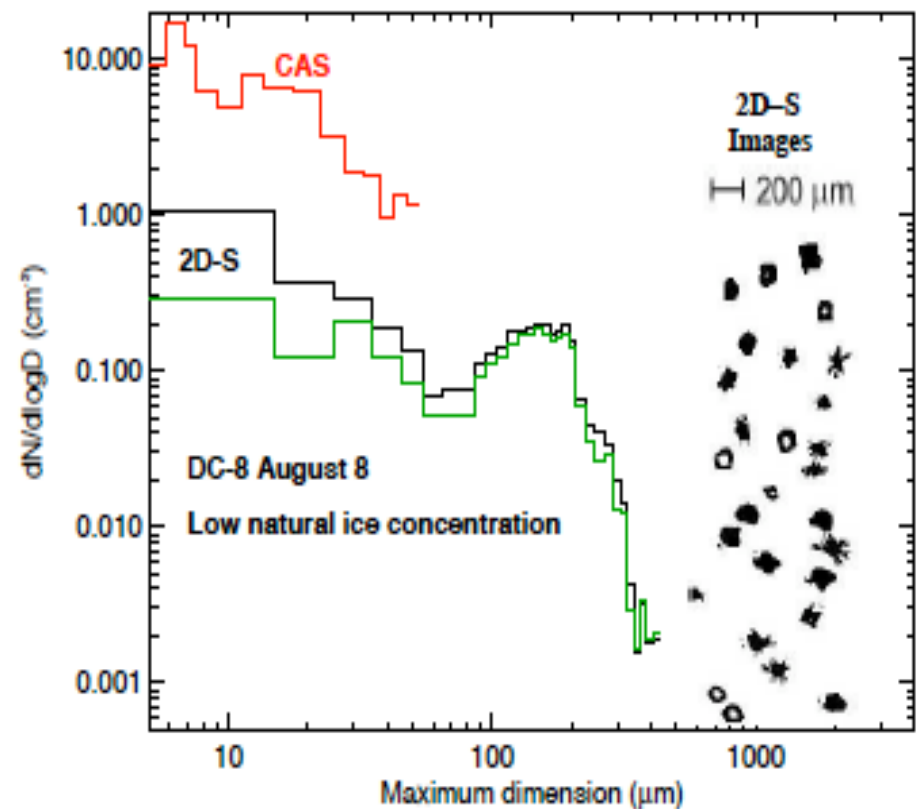
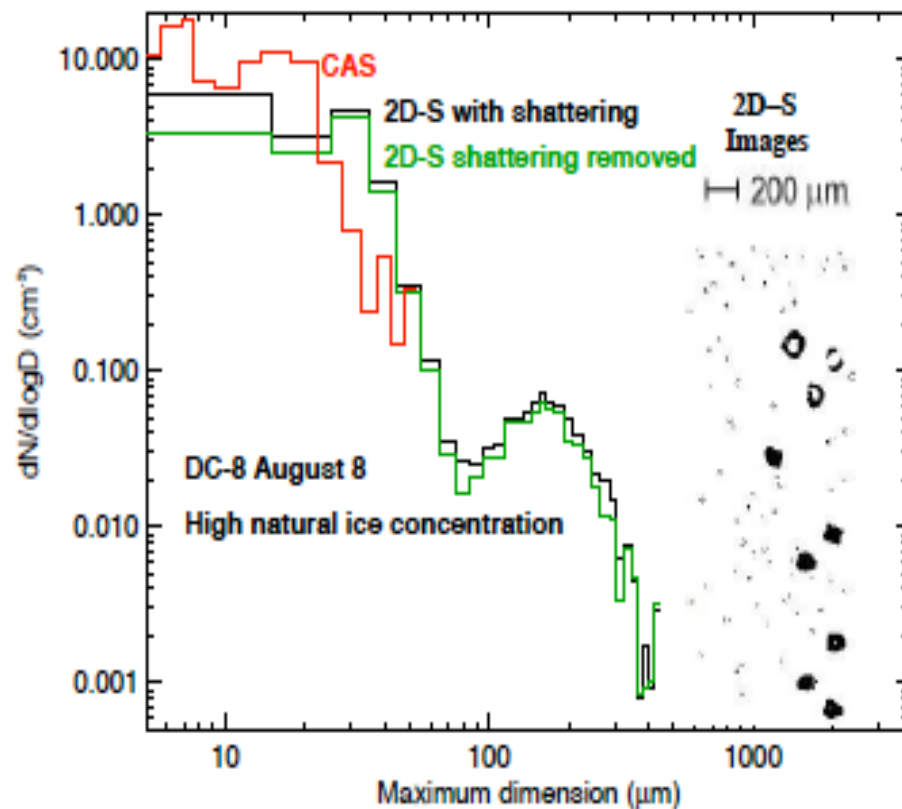


Aug 8. flight designed to compare instruments



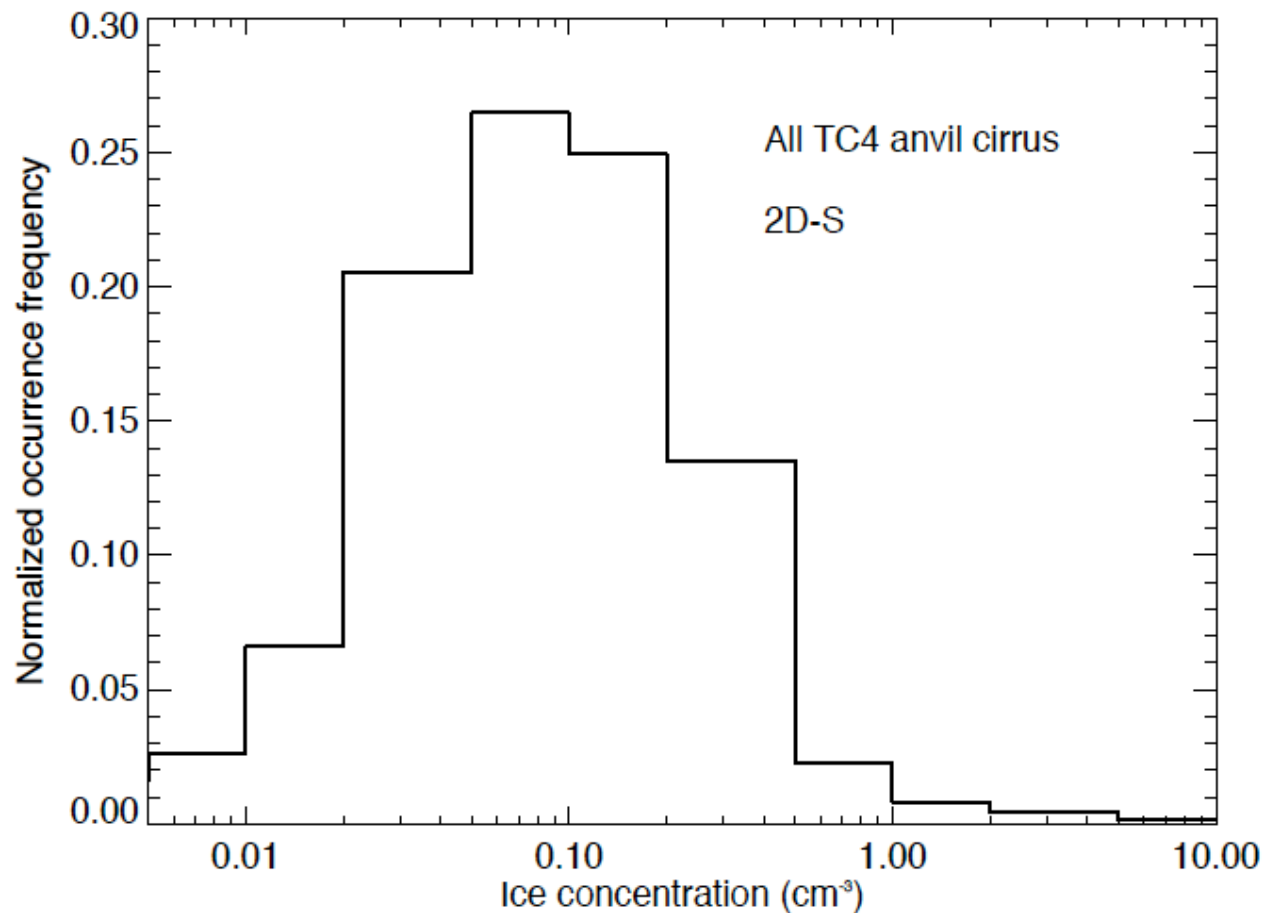
Instruments designed to reduce shattering show fewer small particles.

Jensen et al., ACPD 5321, 2009



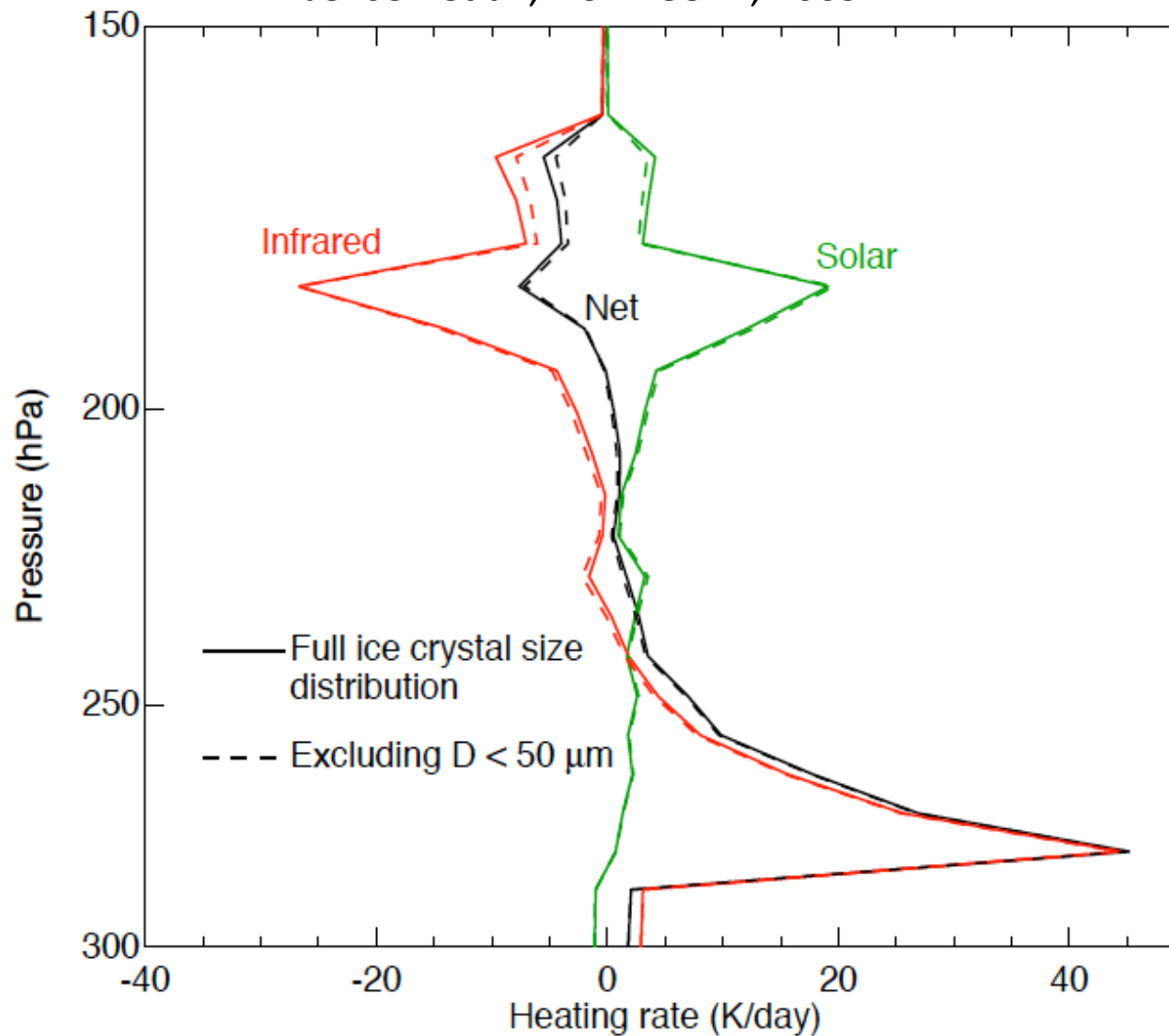
In anvils ice numbers above 1 cm^{-3}
only occurred 1.4% of the time

Jensen et al., ACPD 5321, 2009



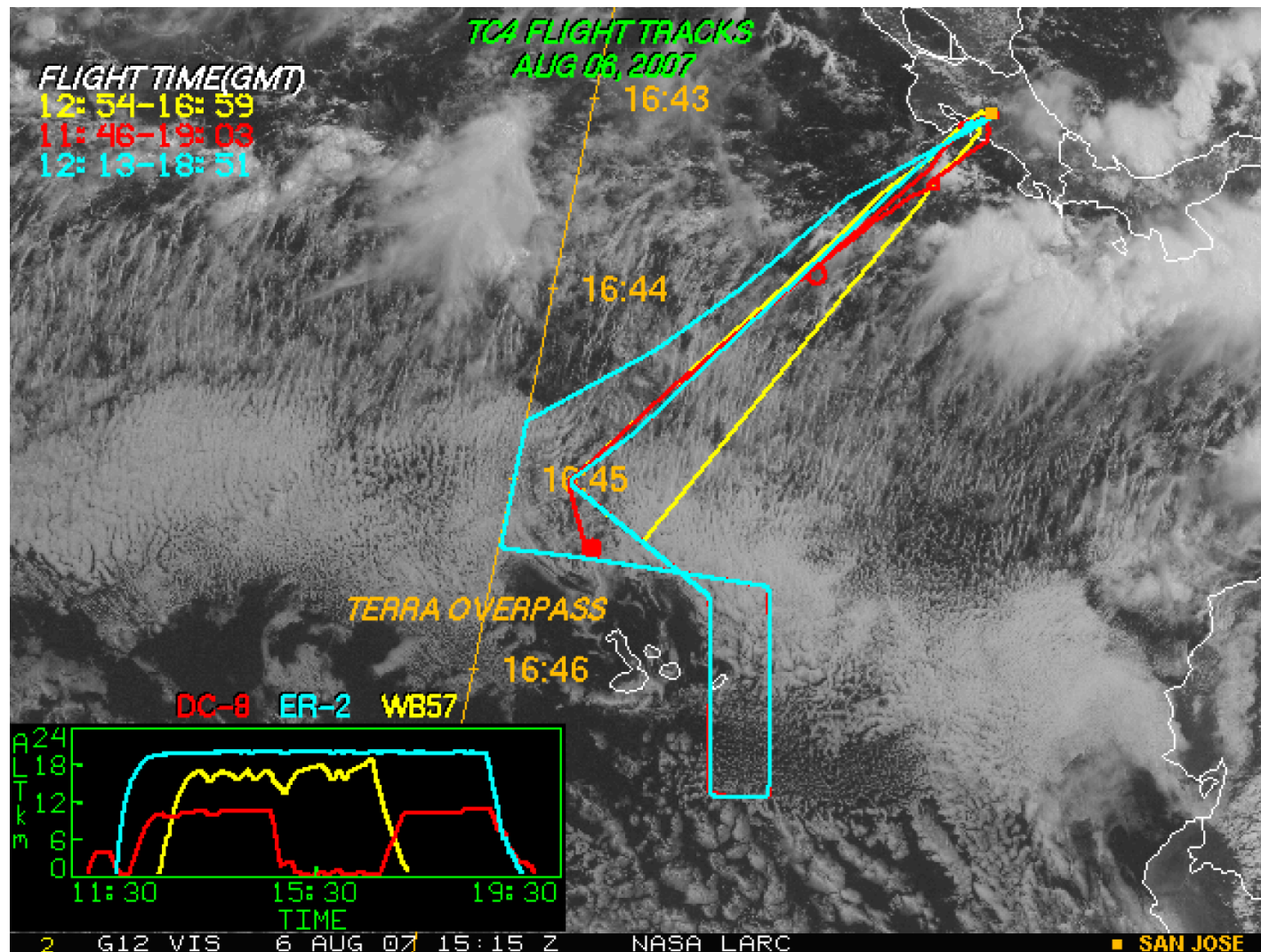
For TC4 anvils, small particles contributed little to radiative heating rates

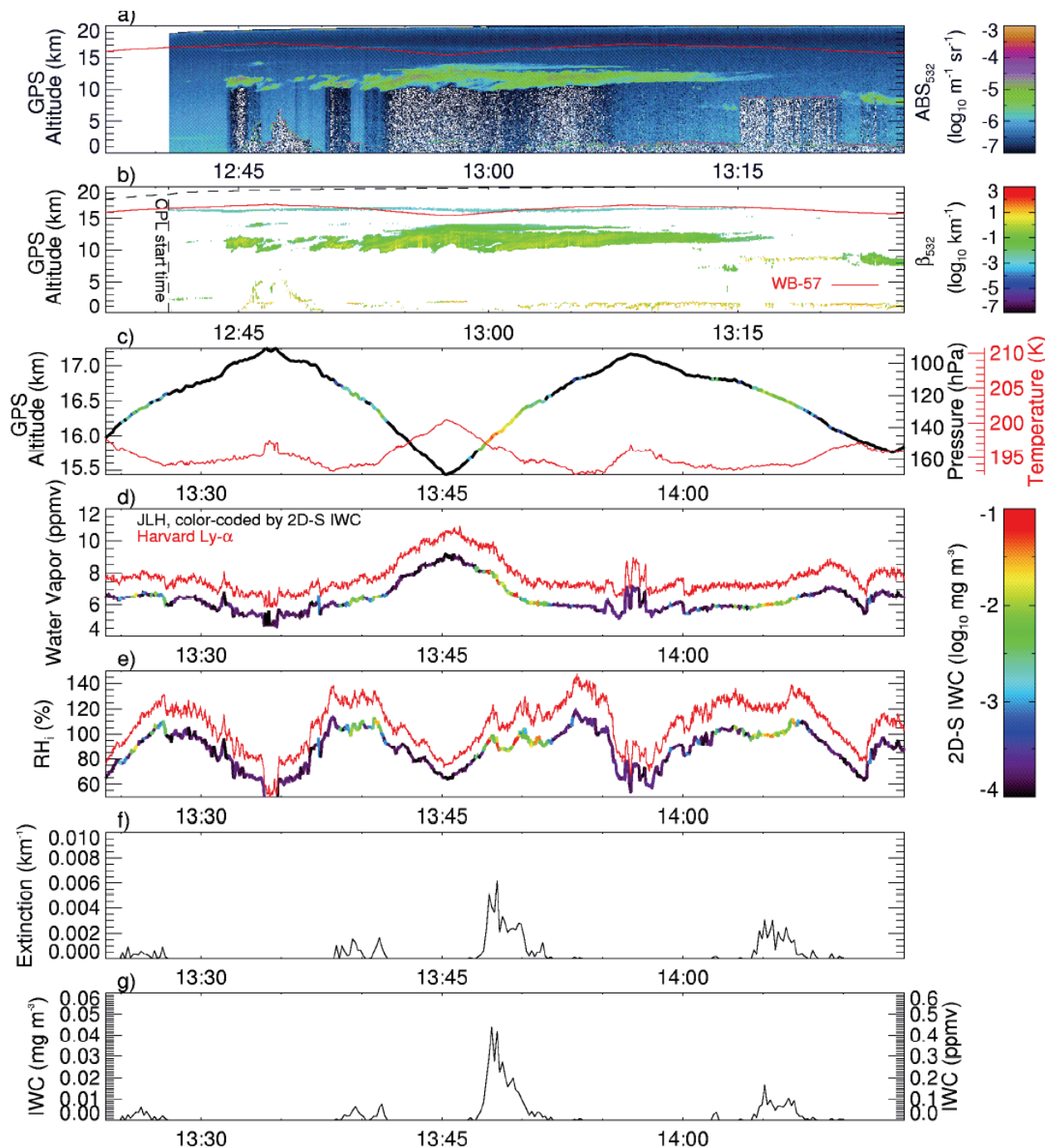
Jensen et al., ACPD 5321, 2009



Flight Tracks for Aug. 6, 2007

subvisible cirrus study



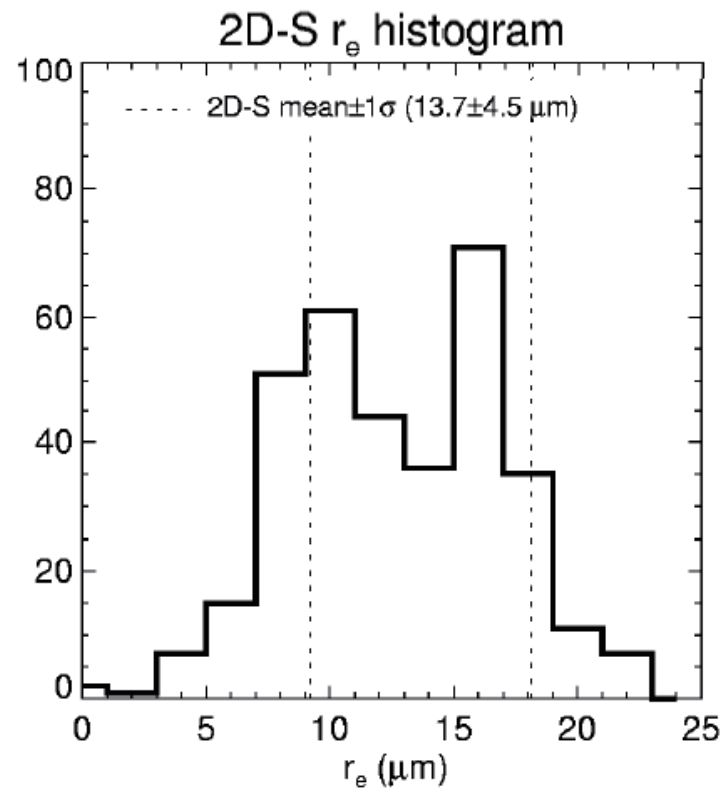
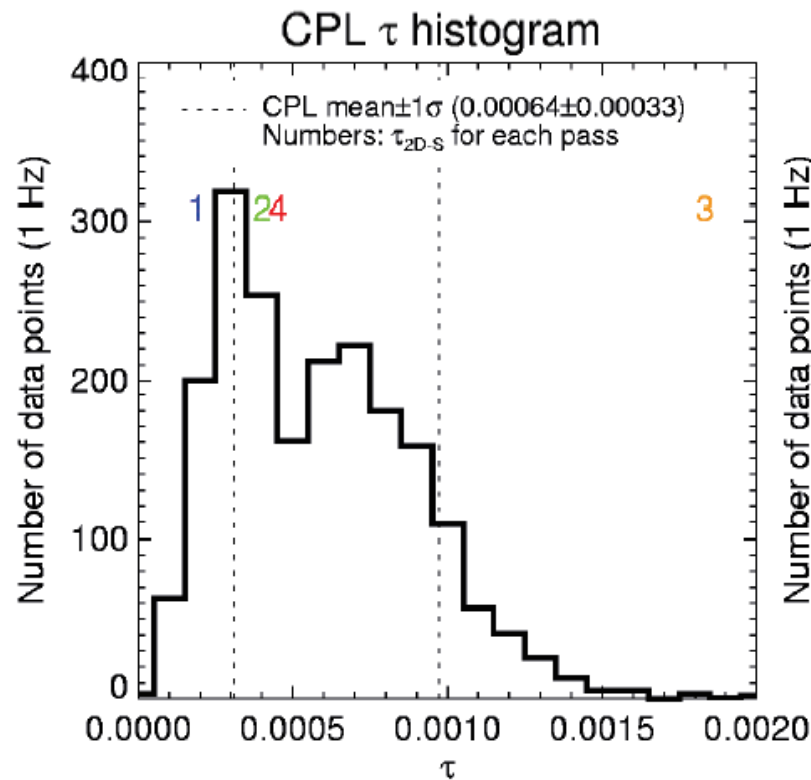
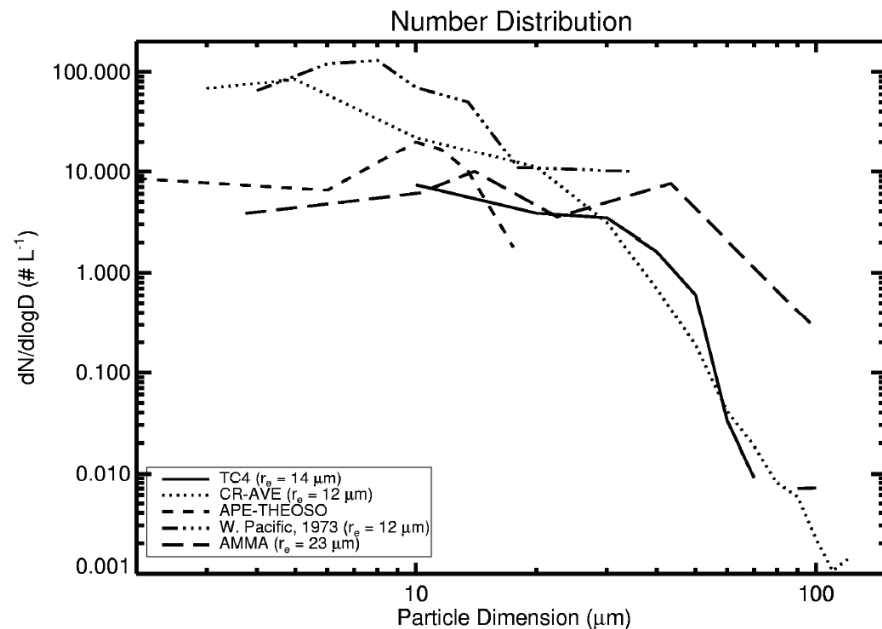


TC4 observations of a subvisible cirrus with ER-2, WB-57F

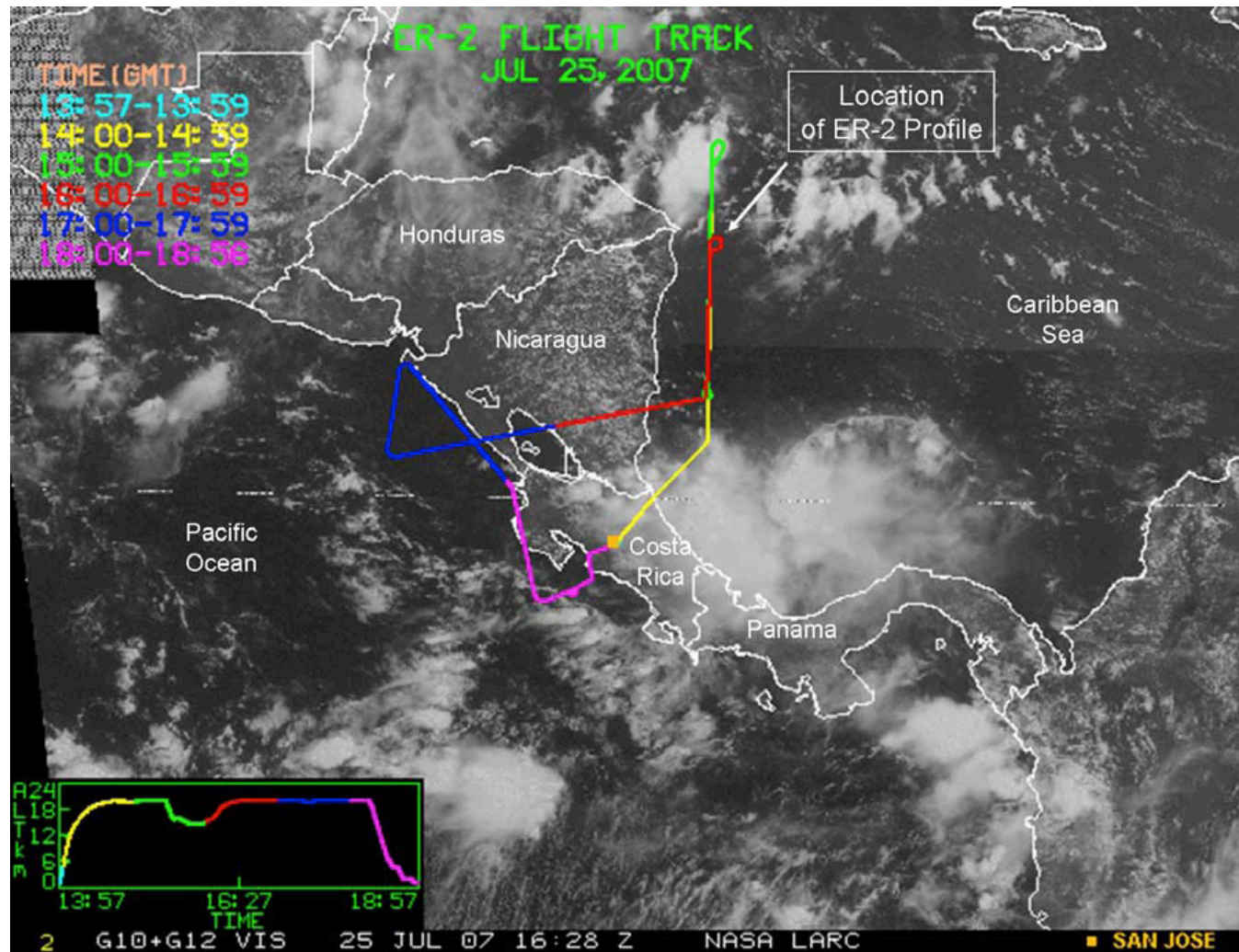
S. Davis et al in press JGR,
2010

Subvisible cirrus properties indicate water removal can occur, define optical properties

S. Davis, JGR in press, 2010

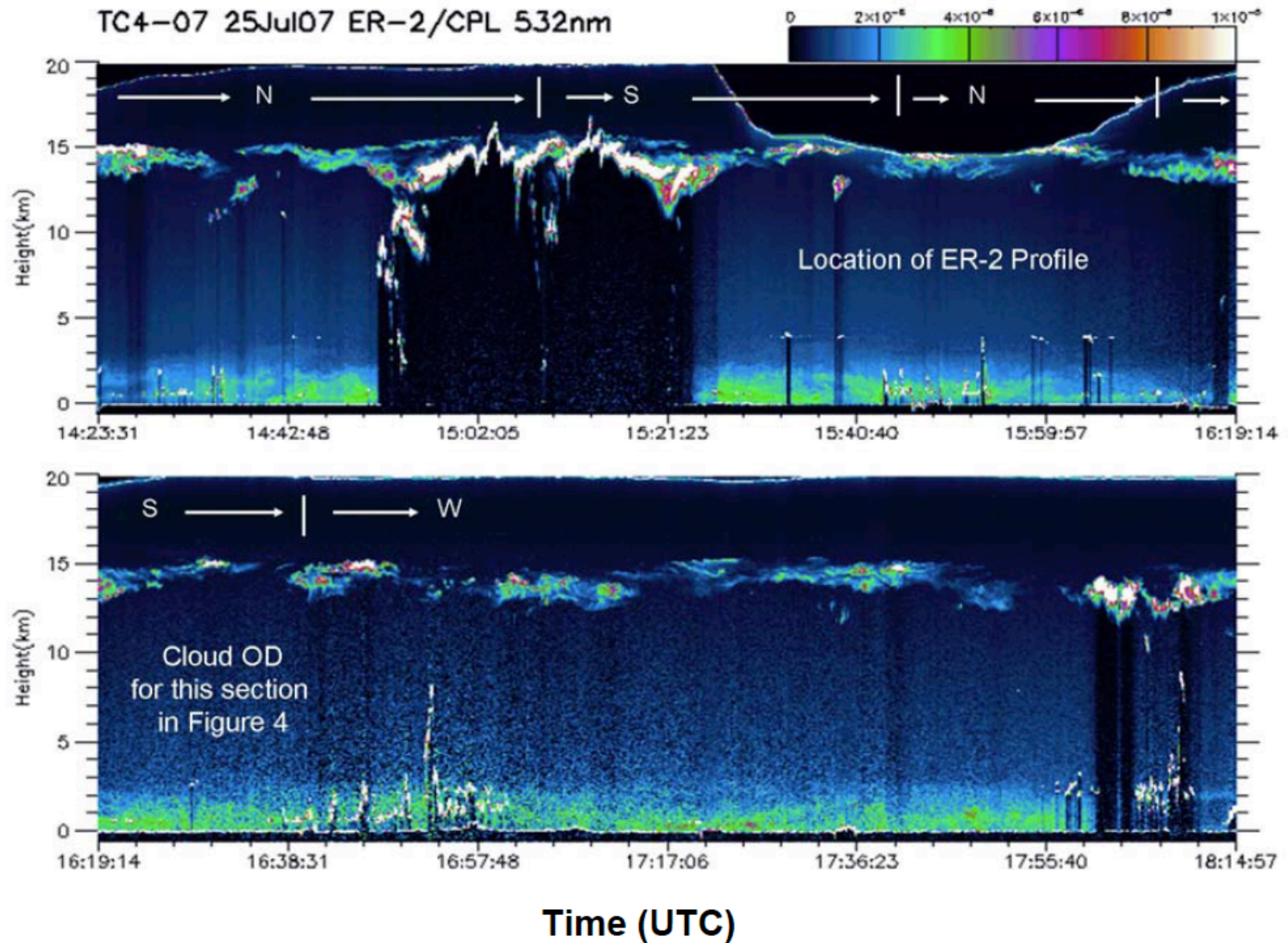


July 25 flight for thin cirrus heating rates



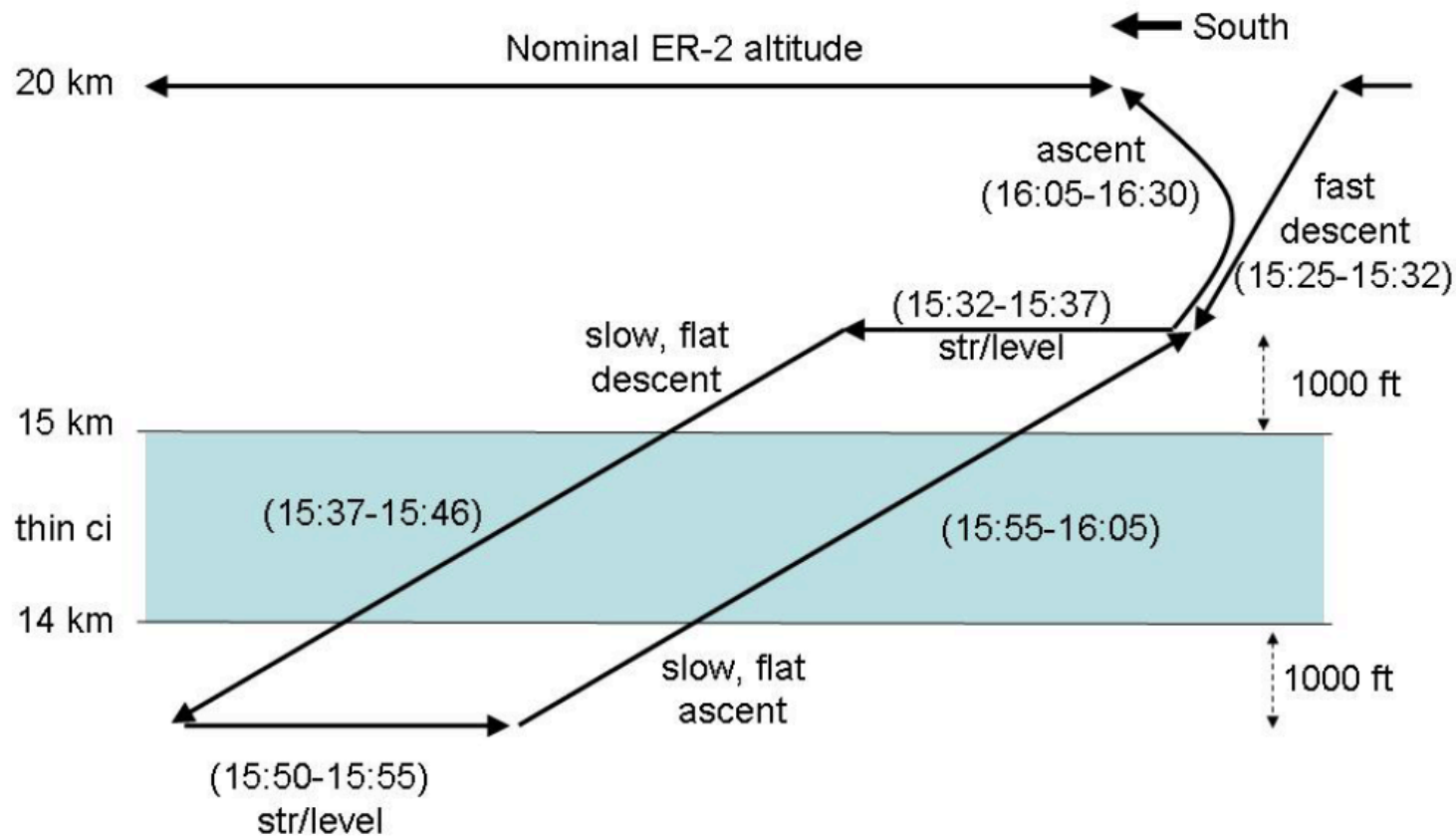
Thin cirrus sampled by ER-2

A. Bucholtz et al, JGR, 2010



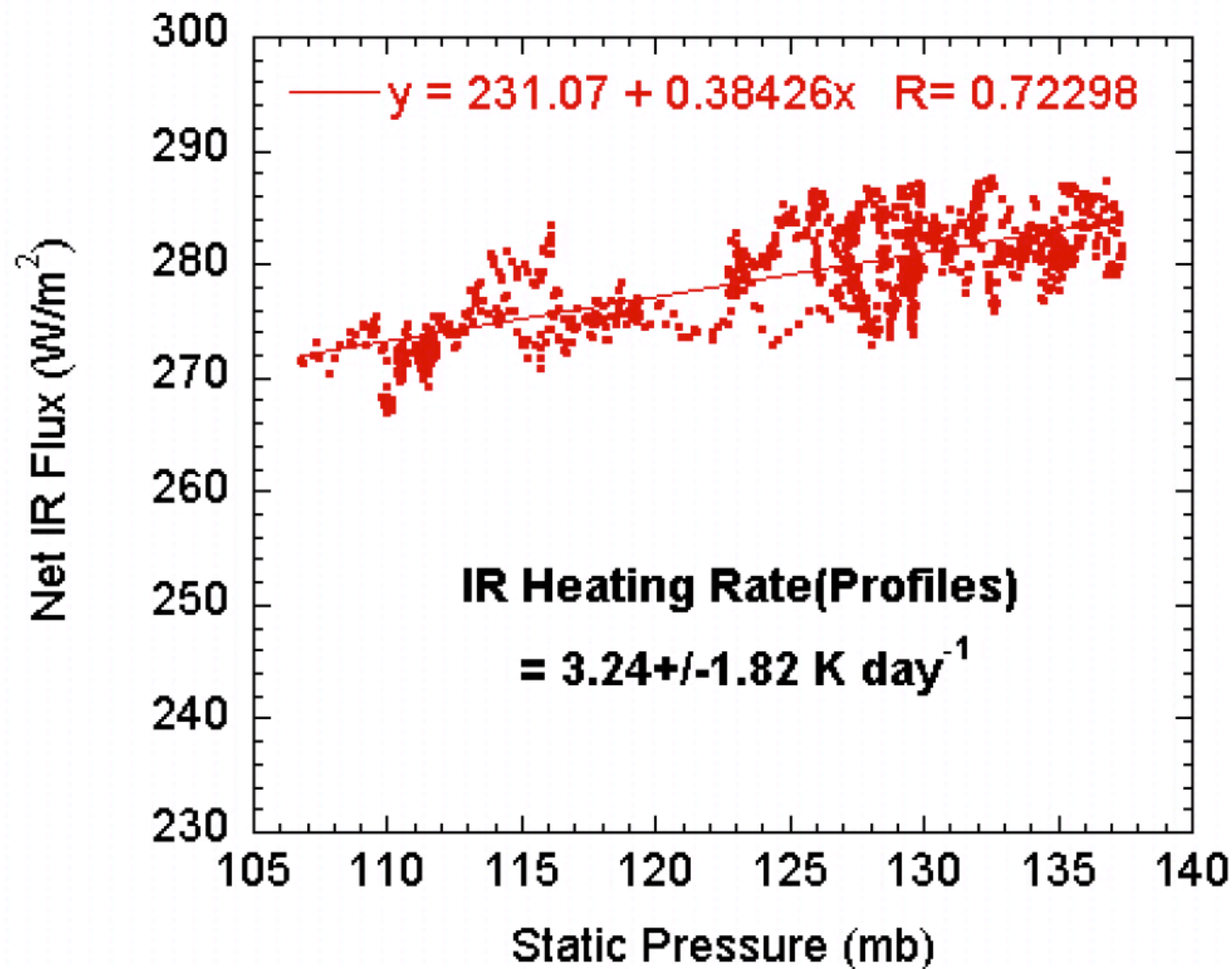
Profile for obtaining heating rate

A. Bucholtz et al, JGR, 2010



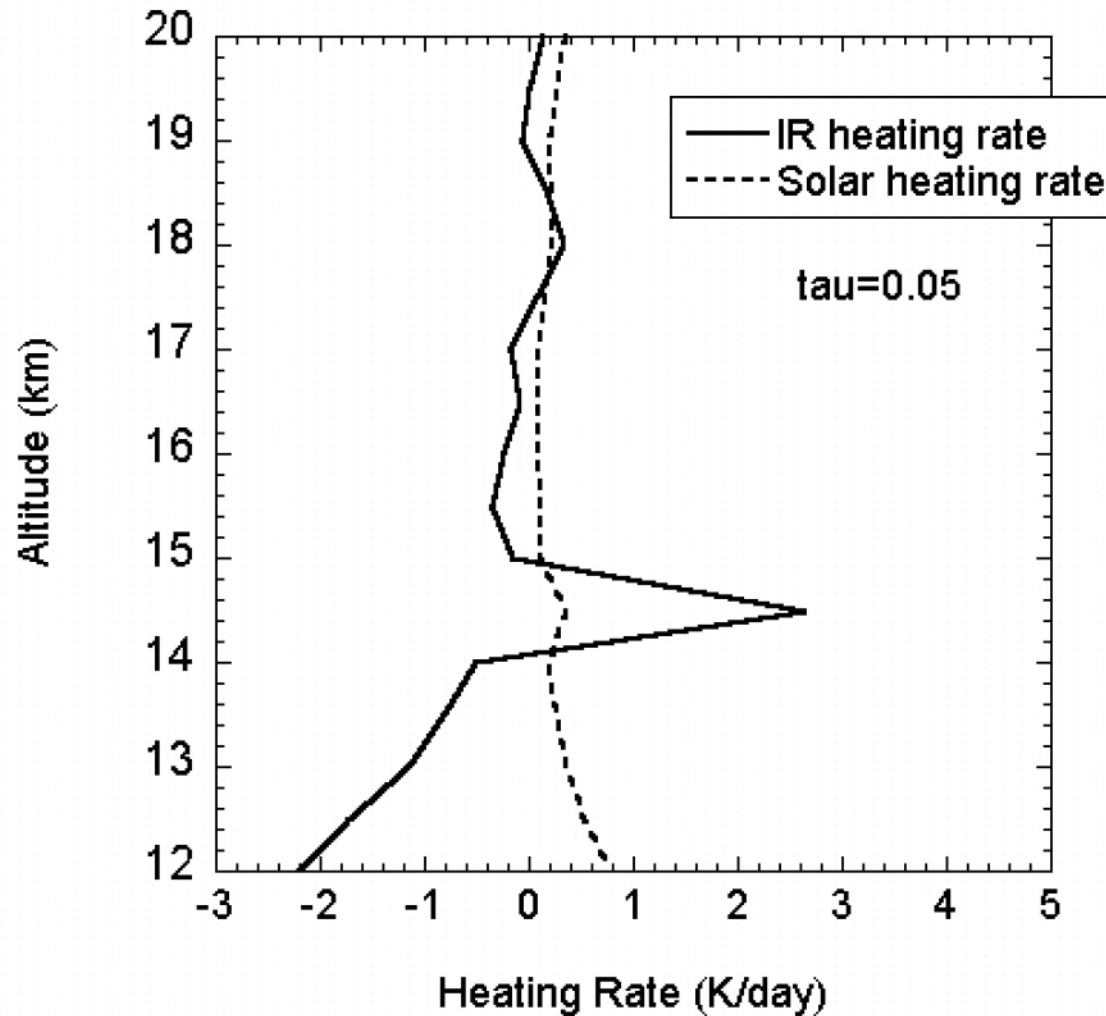
Heating rate from measured IR flux versus pressure

A. Bucholtz et al, JGR, 2010



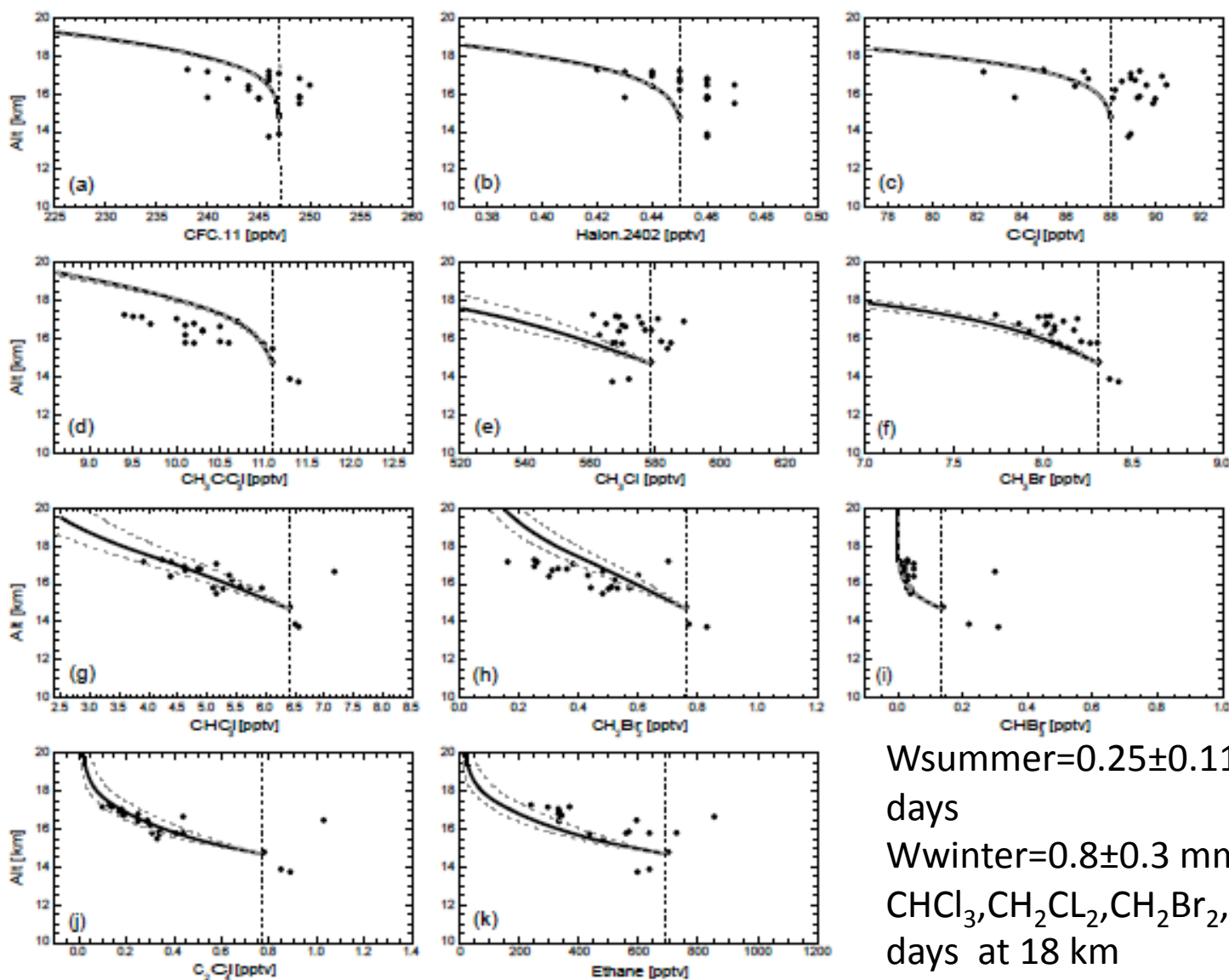
Heating rate calculated from data agrees with measurements

A. Bucholtz et al, JGR, 2010



Vertical distributions of important Cl, Br gases show short lived species can reach the stratosphere

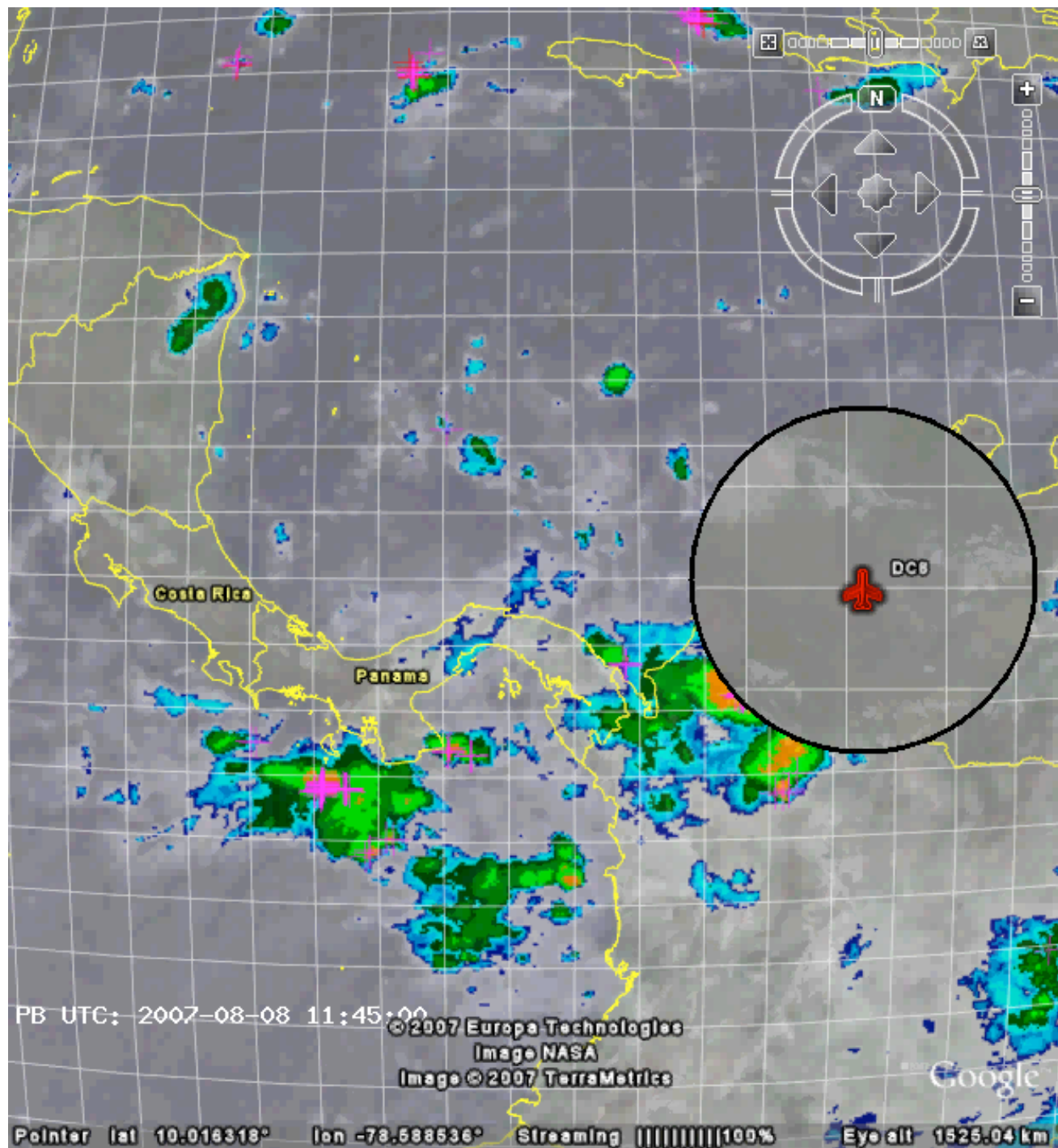
Park et al., ACPD, 6059,2010



Wsummer=0.25±0.11 mm/s; t_t =199 days

Wwinter=0.8±0.3 mm/s; t_t =80 days

CHCl₃, CH₂Cl₂, CH₂Br₂, t_t =294, 273, 186 days at 18 km



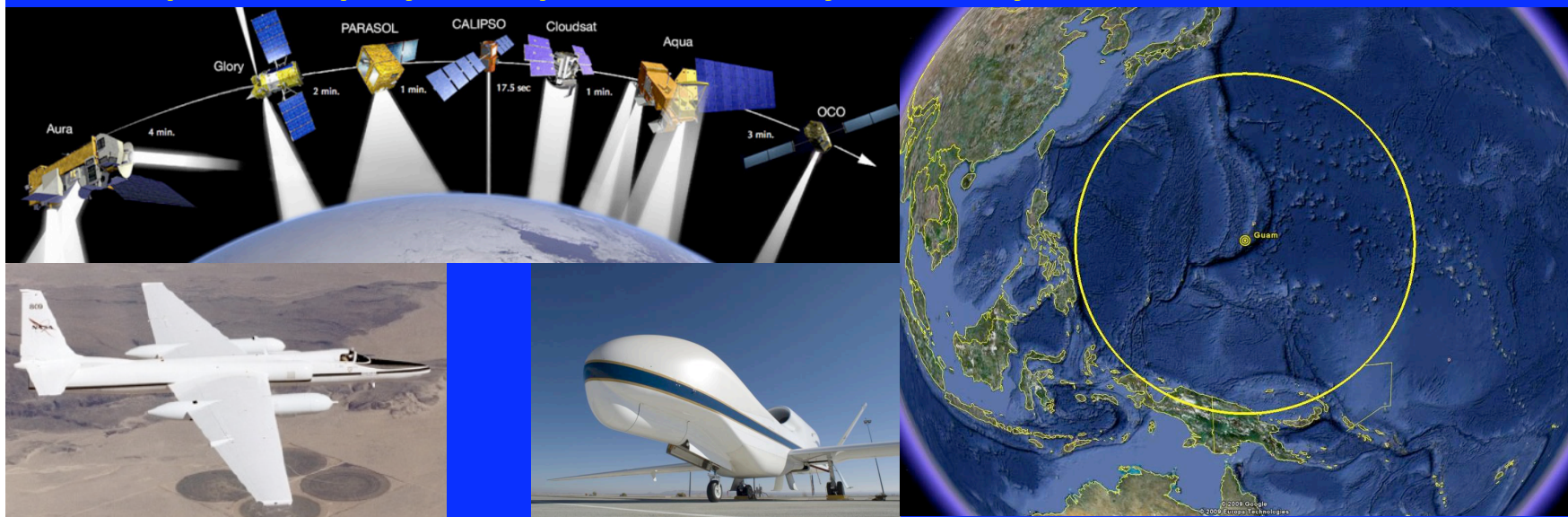
TC4 was first mission to
fully implement in flight
communications and
navigation with NASA
Aircraft using REVEAL and
RTMM

Pacific Atmospheric Composition, Cloud, and Climate Experiment (PAC³E) - Guam phase

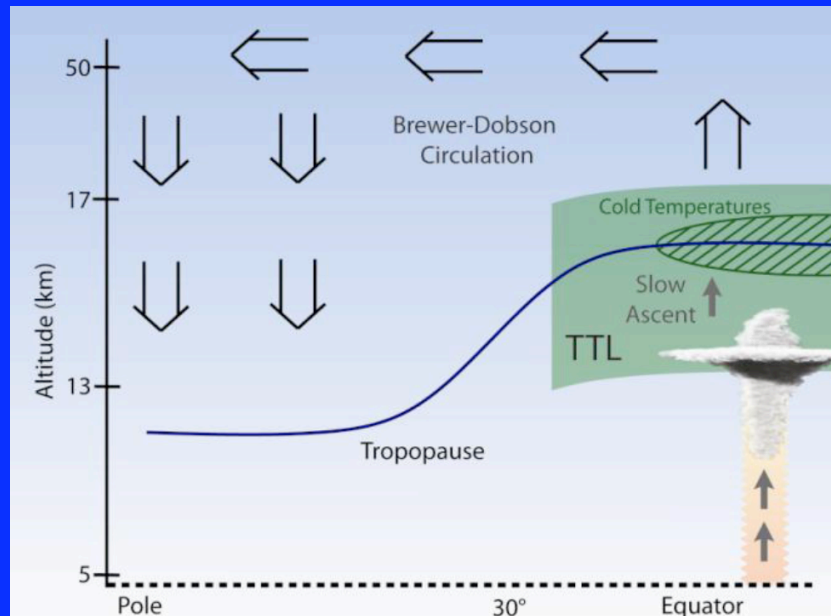
A NASA airborne field campaign focusing on atmospheric composition, clouds, chemistry, and climate over the western Pacific:

- Understanding TTL transport and cloud processes controlling the humidity of air entering the stratosphere
- Understanding the role of brominated species in controlling ozone concentrations in the TTL and lower stratosphere.

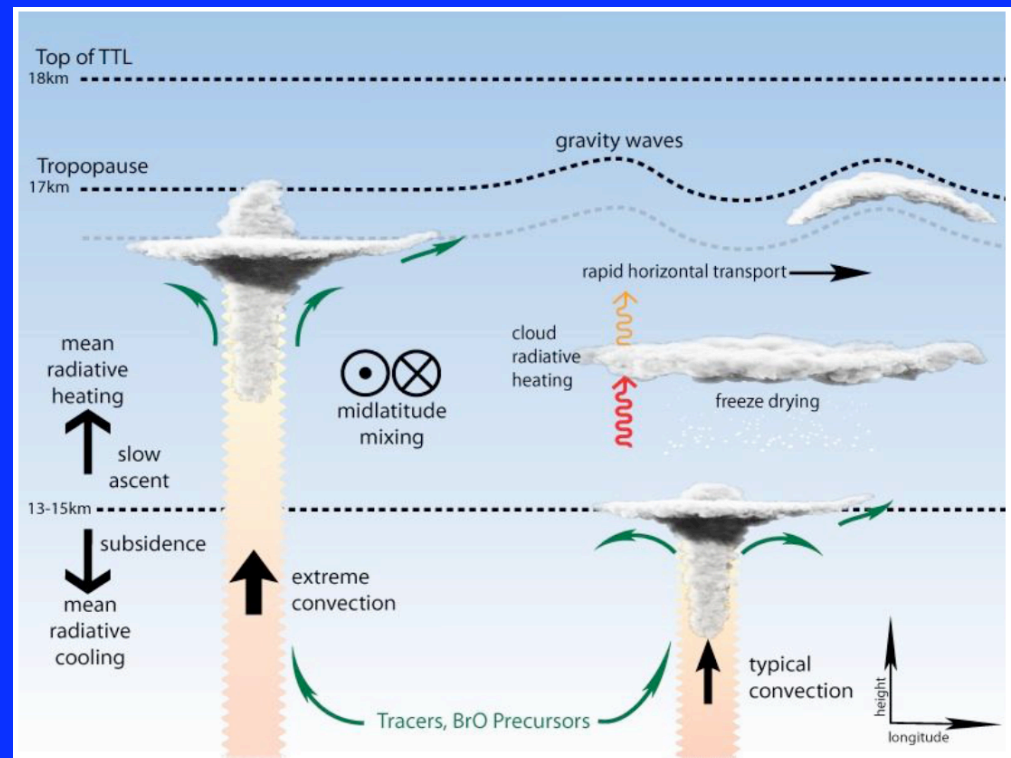
Anticipated deployment period: January-February 2012



Processes occurring in the Tropical Tropopause Layer (TTL) control the chemical composition and humidity of air entering the stratosphere.



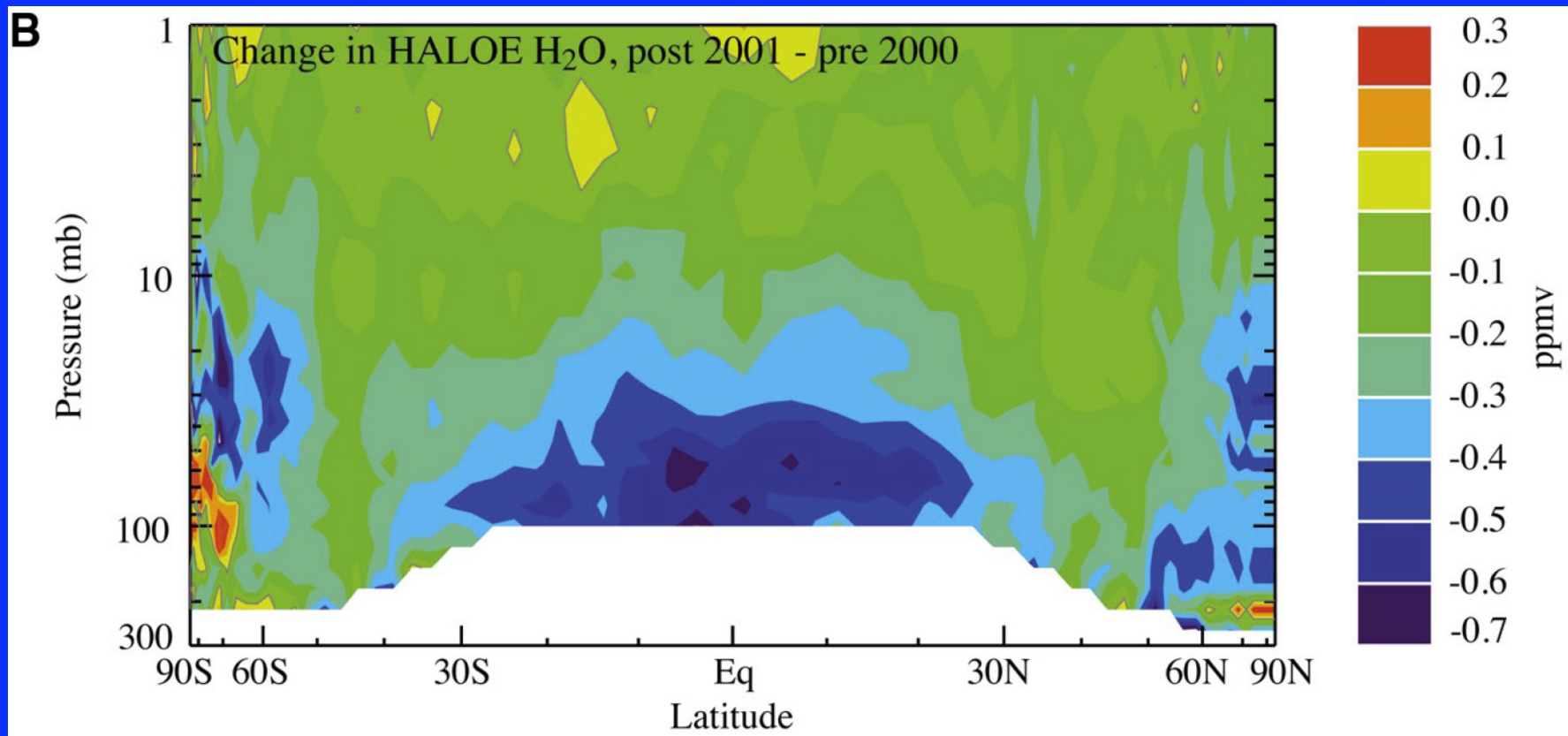
A range of dynamical, chemical, and microphysical processes affect the TTL and stratospheric composition.



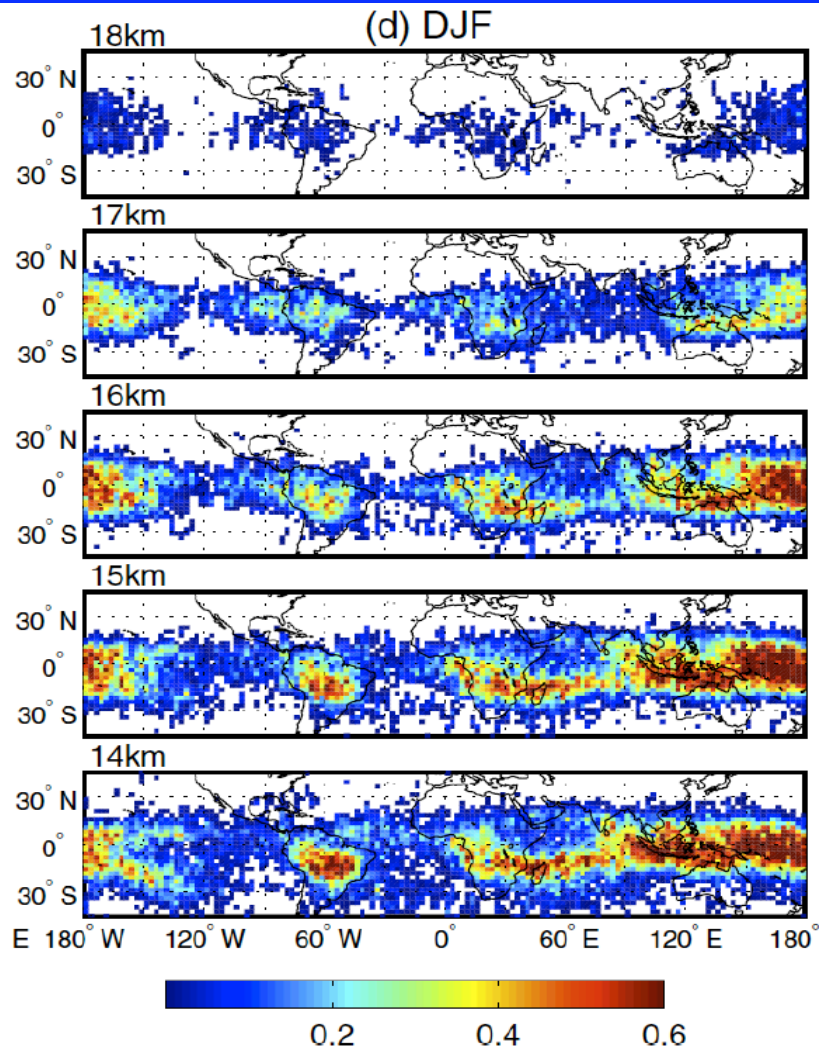
Small changes in stratospheric humidity have been shown to have impacts on radiative forcing and climate comparable to increasing greenhouse gases [Solomon et al., *Science*, 2010].

2001-2005 H₂O vs 1996-2000 H₂O: -0.098 W/m^2

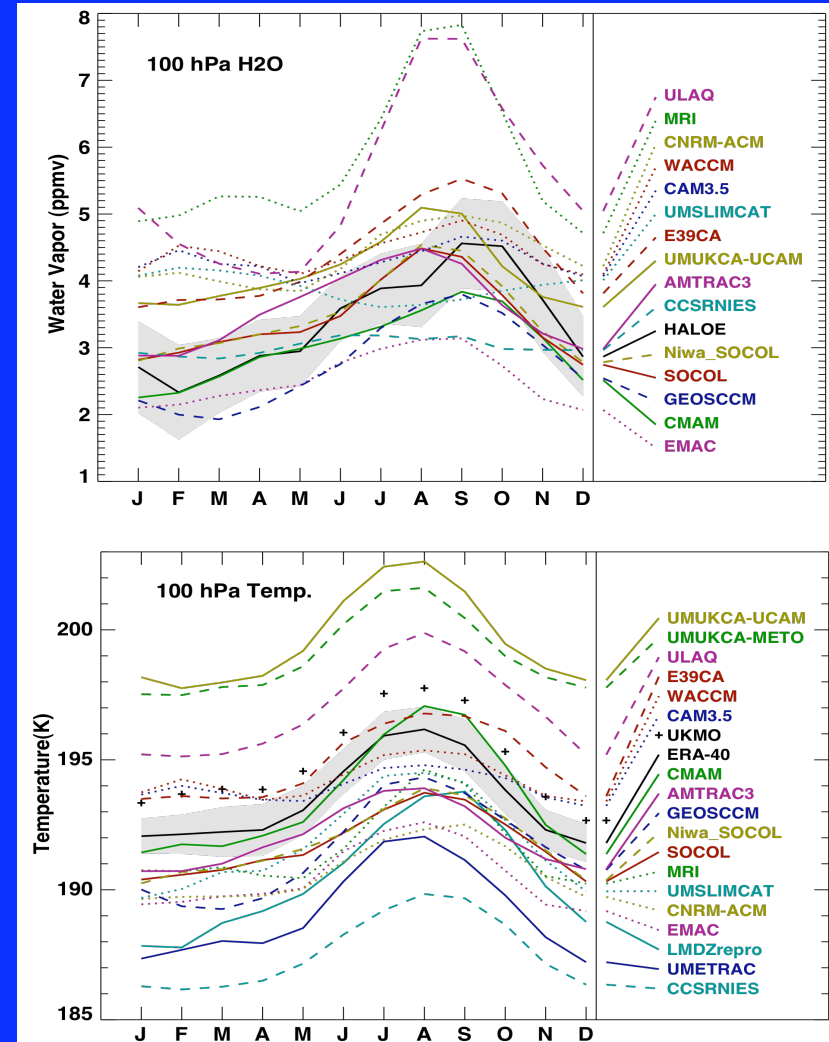
1996-2005 CO₂ increase: $+0.26 \text{ W/m}^2$



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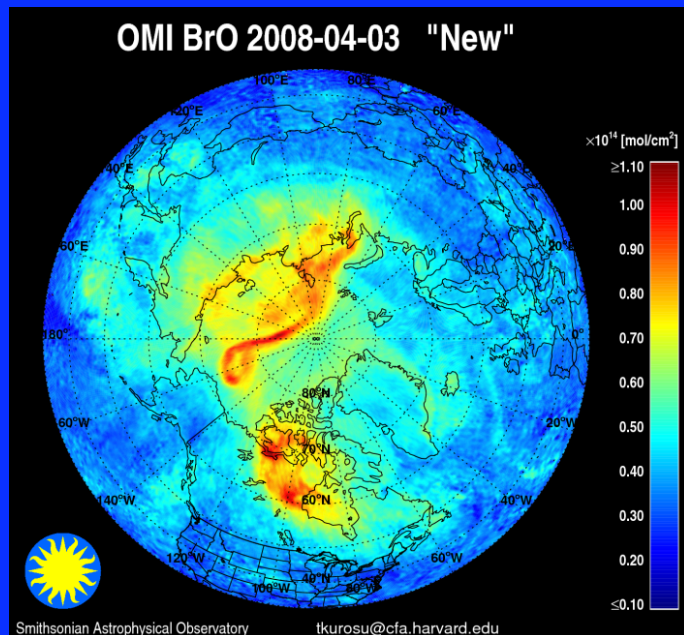


Yang et al., 2009



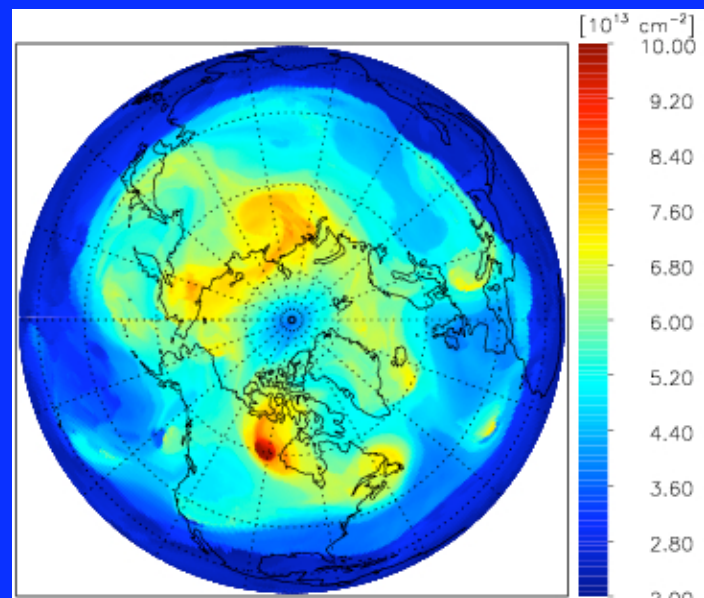
Gettleman et al., 2010

ARCTAS has revolutionized our understanding of atmospheric bromine



OMI BrO: Kurosu & Chance et al.

Model: VSL Br_y = 10 ppt

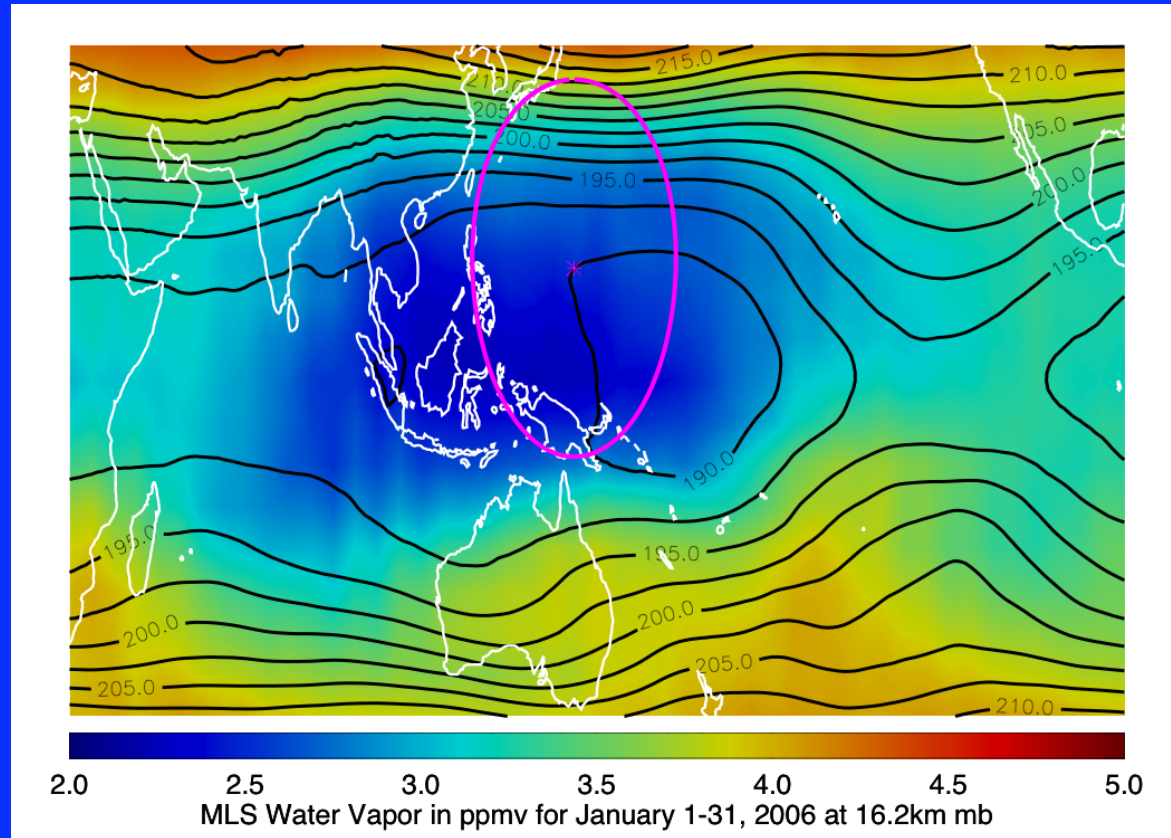


BrO Model: Salawitch & Canty et al.

Prior to ARCTAS it was assumed "hotspots" in total column BrO were caused by the surface "bromine explosion". During ARCTAS, aircraft BrO correlated poorly with satellite BrO. A new theory was put forth that many of the satellite "hotspots" are caused by BrO above the tropopause, for air compressed to high pressure by orographically forced, low altitude tropopause. This theory hinges on the amount of bromine supplied to the stratosphere by VSL (very short lived) sources, which is not well known.

PAC³E seeks to quantify the role of VSL source species on the bromine budget of the UT/LS and define concomitant effects on ozone.

The Boreal winter tropical western Pacific (accessible from Guam) is the region of the planet with the coldest tropopause temperatures and driest lower stratospheric air.



MLS and CALIPSO measurement H_2O , tracers, and clouds will be needed (in combination with the airborne measurements) to understand the transport and dehydration processes.

Major Science Questions:

- 1. What are the physical mechanisms that control the humidity of the stratosphere?***
- 2. What are the physical mechanisms that control long-term changes in tropical upper tropospheric humidity?***
- 3. What controls the formation and maintenance of thin cirrus in the Tropical Tropopause Layer and how does radiative heating in these clouds affect transport through the TTL?***
- 4. What is the role of VSL (very short lived) source species on the bromine budget of the UT/LS, and how is ozone affected by “excess bromine” in these regions of the atmosphere.***

PAC³E Field Campaign Strategy: Maximize the value of satellite data for improving models of atmospheric composition and climate

Satellites: MLS, CALIPSO, MODIS, MISR, OMI, MOPITT, AIRS

• H₂O, CO, ozone, BrO, clouds



Aircraft: ER-2, other high flyers

- Comprehensive in situ chemical and cloud measurements
- Active remote sensing of cloud properties

Models: CTMs, GCMs, microphysical models

Calibration and Validation
Retrieval development
Correlative information
Small scale structure and processes

Model error evaluation
Data assimilation
Diagnostic studies



ER-2 Payload Priorities: 1= required; 2 = desired; 3 = useful

| <u>Gas Phase In Situ</u> | <u>Priority</u> |
|--|-----------------|
| <i>O₃, H₂O, CO, CO₂, NO</i> | 1 |
| <i>HCHO, H₂O₂, CH₃OOH</i> | 1 |
| <i>NMHCs, OVOCs</i> | 1 |
| <i>OH/HO₂/RO₂</i> | 2 |
| <i>BrO</i> | 2 |
| <i>Halocarbons</i> | 2 |
| <i>CH₄</i> | 2 |
| <i>NO₂, NO_y</i> | 2 |
| <i>HNO₃, PANs, HO₂NO₂</i> | 2 |
| <i>HCN, CH₃CN</i> | 2 |
| <i>SO₂</i> | 2 |
| <i>N₂O</i> | 3 |
| <i>HOBr, ClO, HOCl</i> | 3 |
| <i>RONO₂</i> | 3 |
| <i>NH₃</i> | 3 |
| <i>Organic Acids</i> | 3 |
| <i>Speciated Hg</i> | 3 |

| <u>Aerosol and Cloud In Situ</u> | <u>Priority</u> |
|--|-----------------|
| <i>Aerosol number</i> | 1 |
| <i>Aerosol size distribution</i> | 1 |
| <i>Aerosol composition</i> | 2 |
| <i>Ice crystal size distribution (and phase)</i> | 1 |
| <i>Condensed Water Content</i> | 1 |
| <i>Ice crystal habit</i> | 1 |

| <u>Remote Sensing</u> | <u>Priority</u> |
|---|-----------------|
| <i>Aerosol and cloud extinction (nadir/zenith)</i> | 1 |
| <i>Aerosol depolarization (nadir/zenith)</i> | 2 |
| <i>Solar and IR radiative fluxes (nadir/zenith)</i> | 1 |

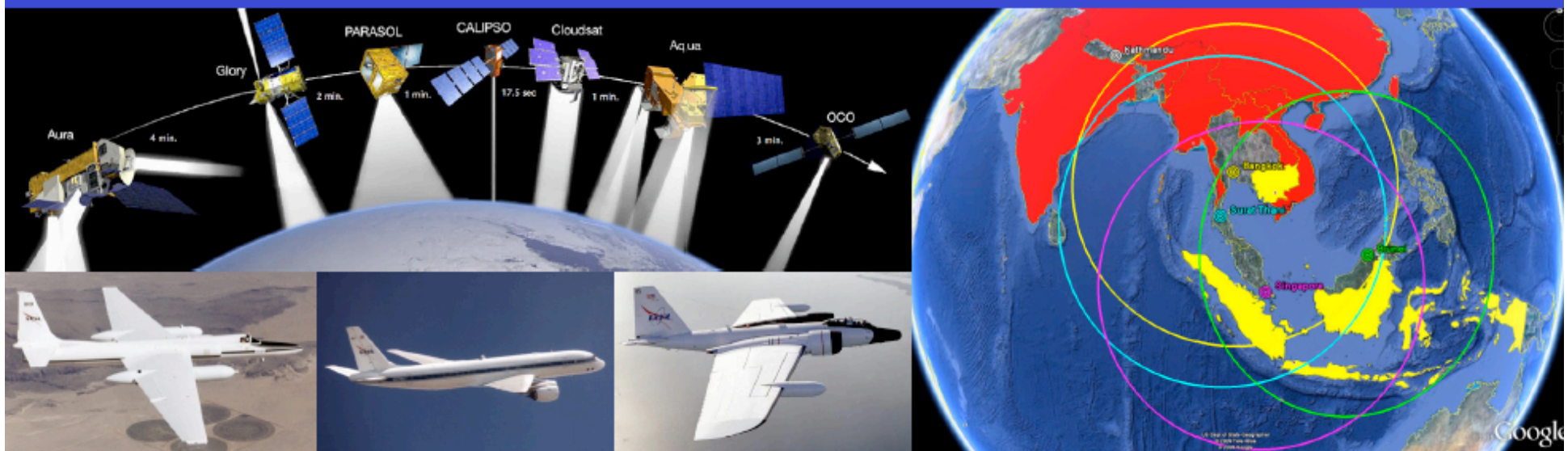
| <u>Meteorology</u> | <u>Priority</u> |
|---------------------------|-----------------|
| <i>State, winds, etc.</i> | 1 |

Pacific Atmospheric Composition, Cloud, and Climate Experiment (PAC³E) - Southeast Asia Phase

A NASA airborne field campaign focusing on atmospheric composition, chemistry, and climate over Southeast Asia related to:

- Asian monsoon circulation impacts on upper troposphere/lower stratosphere composition**
- Biomass burning impacts on atmospheric composition, radiation, and clouds**

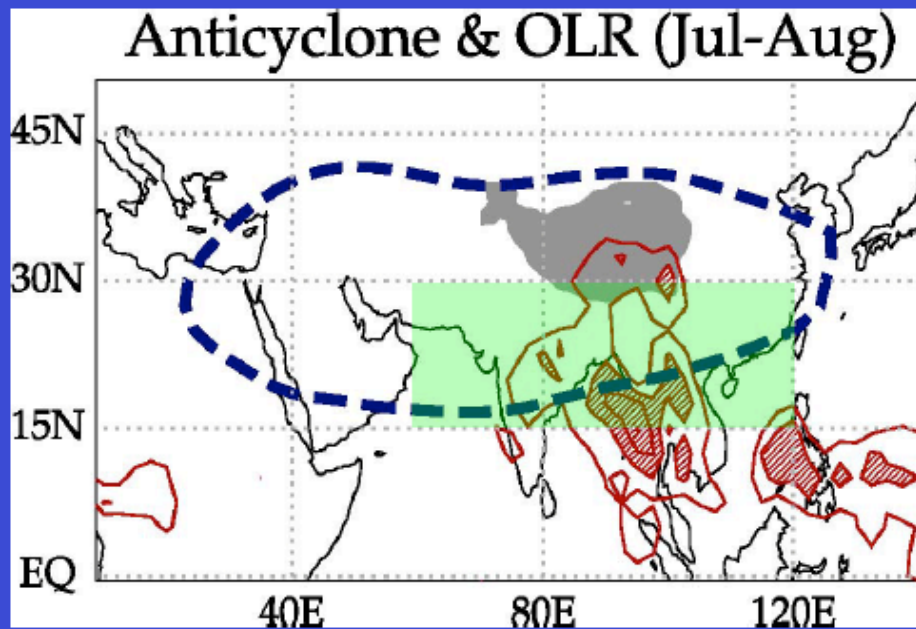
Anticipated deployment period: August - September 2012



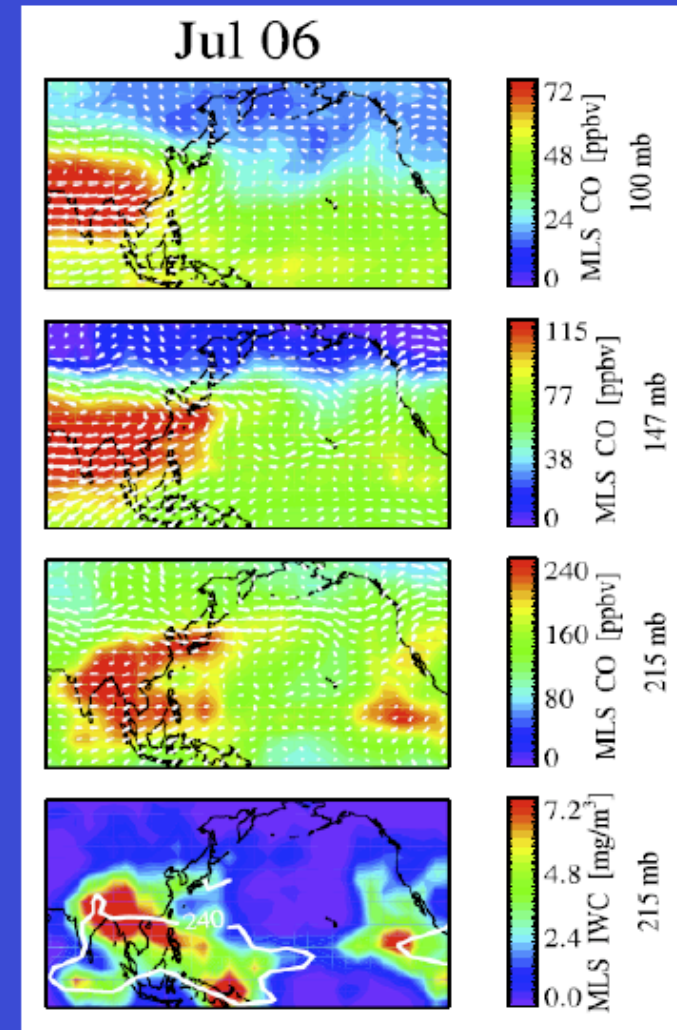
The Asian monsoon anticyclone is believed to be a dominant pathway for transport from the troposphere into the stratosphere.

Satellite observations from MLS and ACE show enhanced concentrations of tropospheric tracers within the Asian monsoon anticyclone.

The role of overshooting convection versus slow ascent of convective outflow from lower altitudes is a point of current debate.



Park et al., JGR, 2007

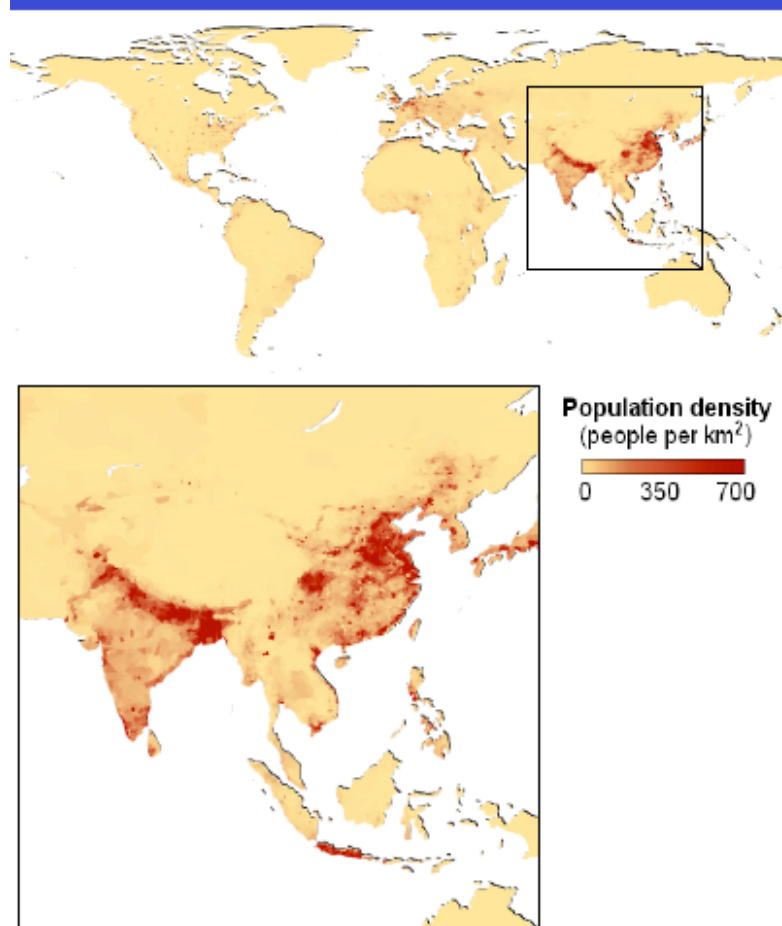


Jiang et al., GRL, 2007

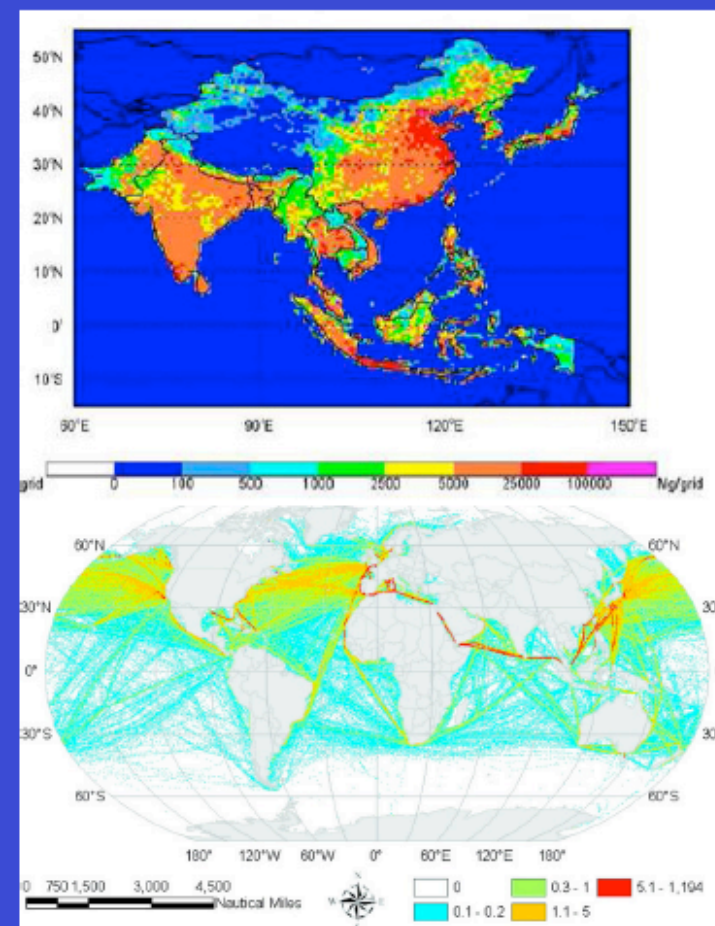
Convection over Southeast Asia and Indonesia is associated with uniquely diverse and rapidly changing emissions.

Population and economic development are primary drivers for anthropogenic emissions which are increasing rapidly in Southeast Asia

Strong anthropogenic sources are intermingled with strong biogenic and natural emissions across both terrestrial and marine environments



Anthropogenic VOCs
Zhang et al., ACP, 2009



Shipping emissions
Wang et al., ES&T, 2008

Asian monsoon convection and Indonesian biomass burning have relevance to both climate and air quality.

- Convective pumping of pollutants into the UT/LS influences the photochemistry of ozone at altitudes where its greenhouse forcing potential is greatest.
- Properties of cirrus anvils (e.g., cloud-top height, persistence and ice particle radius) may also be influenced by pollution.
- Smoke aerosols from fires can have a large influence on the tropical radiation budget, cloud properties, and tropospheric oxidation chemistry
- At tropical latitudes, local pollution effects are more pronounced as more intense sunlight and higher humidity allow pollution chemistry to proceed at a faster pace.
- In contrast to mid-latitudes, where frontal passages play a dominant role in the clearing of pollution, deep convection takes on a prominent role in ventilating the tropical polluted boundary layer, leading to long-range transport of pollution at higher altitudes.

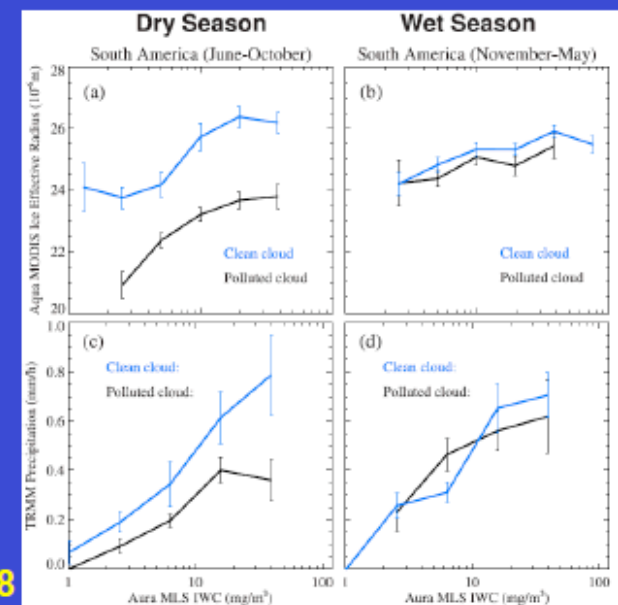
Satellite observations over this region require both validation and correlative observations to maximize their utility for understanding influences of convective redistribution, changing emissions, and biomass burning on atmospheric composition.

MLS: While the morphology of MLS CO (version 2) is believed to be robust, observations at 215 hPa exhibit a positive bias. Detailed observations of convective impacts on UT/LS composition are needed to assess the utility of CO observed from space as a proxy for expected enhancements in other related pollutants.

OCO: Observations of the vertical distribution of CO₂ along with detailed composition are needed to interpret future OCO observations in this region of diverse anthropogenic and biogenic influences.

Glory, CALIPSO, MODIS, and MISR: Detailed aerosol and radiation measurements are needed to better understand the direct radiative impact of aerosols along with detailed composition to enable better application of techniques to differentiate “polluted” and “clean” clouds in satellite analyses.

Jiang et al., GRL, 2008



Major Science Questions:

- 1. How are pollutant emissions in the tropics redistributed via deep convection throughout the troposphere?***
- 2. What is the evolution of gases and aerosols in deep convective outflow and what are the implications for the UT/LS chemistry?***
- 3. What influence do aerosols from anthropogenic pollution and biomass burning exert on local meteorology through changes in the local temperature structure of the atmosphere and cloud formation?***
- 4. TTL transport (topic of discussion for steering group)***

Aircraft Payloads: 1= required; 2 = desired; 3 = useful

HIAPER not prioritized, but "X" denotes proposed payload for DC-3 campaign

| <u><i>Gas Phase In Situ</i></u> | <u><i>DC-8</i></u> | <u><i>ER-2</i></u> | <u><i>NSF/NCAR GV</i></u> | <u><i>WB-57</i></u> |
|--|--------------------|--------------------|---------------------------|---------------------|
| <i>O₃, H₂O, CO, CO₂</i> | 1 | 1 | X | 1 |
| <i>NO, NMHCs</i> | 1 | 2 | X | 1 |
| <i>CH₄, OVOCs</i> | 1 | 2 | X | 2 |
| <i>OH/HO₂/RO₂</i> | 1 | 2 | X | 2 |
| <i>HCHO, H₂O₂, CH₃OOH</i> | 1 | 2 | X | 2 |
| <i>BrO</i> | 2 | 2 | X | 2 |
| <i>Halocarbons</i> | 2 | 2 | | 2 |
| <i>NO_y</i> | 2 | 2 | X | 2 |
| <i>NO₂</i> | 2 | 3 | | 3 |
| <i>HNO₃, PANs, HO₂NO₂</i> | 2 | 3 | X | 3 |
| <i>HCN, CH₃CN</i> | 2 | 3 | | 3 |
| <i>SO₂, H₂SO₄</i> | 2 | 3 | X | 3 |
| <i>Organic Acids</i> | 3 | 3 | X | 3 |
| <i>N₂O</i> | 3 | 3 | X | 3 |
| <i>HOBr, ClO, HOCl</i> | 3 | 3 | | 3 |
| <i>RONO₂</i> | 3 | 3 | | 3 |
| <i>NH₃</i> | 3 | 3 | | 3 |
| <i>Speciated Hg</i> | 3 | 3 | | 3 |

Aircraft Payloads: 1= required; 2 = desired; 3 = useful

HIAPER not prioritized, but "X" denotes proposed payload for DC-3 campaign

| <u>Aerosol and Cloud In Situ</u> | <u>DC-8</u> | <u>ER-2</u> | <u>NSF/NCAR GV</u> | <u>WB-57</u> |
|---|--------------------|--------------------|---------------------------|---------------------|
| <i>Aerosol number</i> | 1 | | | 1 |
| <i>Aerosol size distribution</i> | 1 | | X | 1 |
| <i>Optical properties (scattering/absorption)</i> | 1 | | | 1 |
| <i>Aerosol hygroscopicity , f(RH)</i> | 1 | | | 2 |
| <i>Aerosol composition, inorganic</i> | 1 | | | 2 |
| <i>Aerosol composition, organic</i> | 1 | | | 2 |
| <i>Aerosol composition, BC</i> | 1 | | | 3 |
| <i>Cloud condensation nuclei (CCN)</i> | 1 | | | 2 |
| <i>Condensed Water Content</i> | 1 | | X | 3 |
| <i>Size-resolved aerosol composition</i> | 2 | | | 3 |
| <i>Hydrometeor size distribution</i> | 2 | | X | 3 |
| <i>Aerosol gravimetric mass</i> | 2 | | | 2 |
| <i>Aerosol volatility</i> | 3 | | | 3 |
| <i>Cloud water chemistry</i> | 3 | | | 3 |
| <i>Radionuclides (Rn222, Be7, Pb210)</i> | 3 | | | 3 |
| <i>CVI, 2D-S/CPI, 2D-C, SID2H</i> | | | X | |

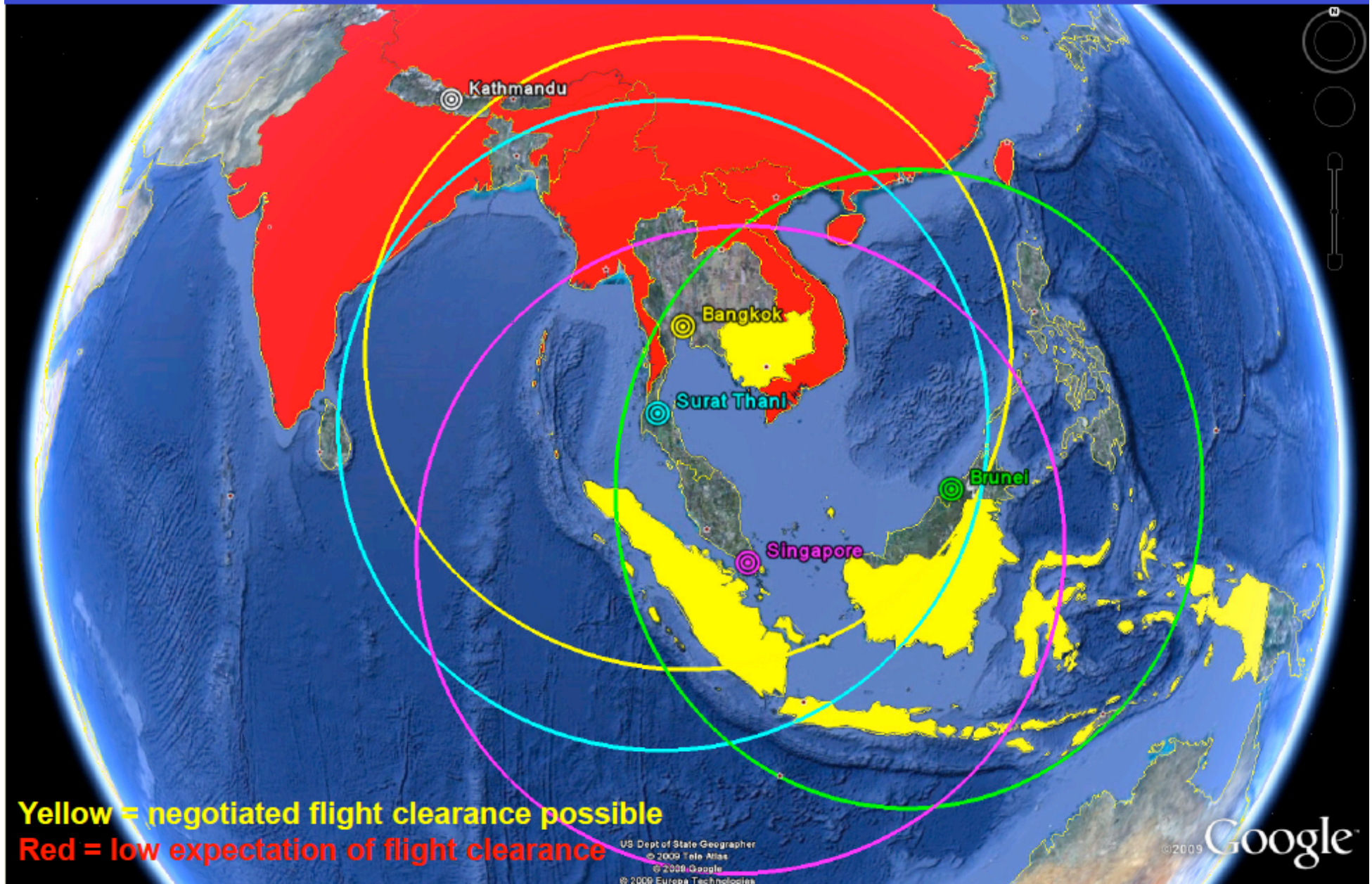
Aircraft Payloads: 1= required; 2 = desired; 3 = useful

HIAPER not prioritized, but "X" denotes proposed payload for DC-3 campaign

| <u>Remote Sensing and Radiation</u> | <u>DC-8</u> | <u>ER-2 (nadir only)</u> | <u>NSF/NCAR GV</u> | <u>WB-57</u> |
|--|-------------|--------------------------|--------------------|--------------|
| <i>UV spectral actinic flux</i> | 1 | | X | 1 |
| <i>Ozone lidar (nadir/zenith)</i> | 1 | | | |
| <i>Hyperspectral solar flux</i> | 1 | 1 | | |
| <i>Broadband flux (nadir/zenith; solar/IR)</i> | 1 | 1 | | |
| <i>Multispectral optical depth profiles</i> | 1 | 1 | | |
| <i>Aerosol extinction profile (nadir/zenith)</i> | 1 | 1 | | |
| <i>Aerosol backscatter (nadir/zenith)</i> | 1 | 1 | | |
| <i>Aerosol depolarization (nadir/zenith)</i> | 1 | 1 | | |
| <i>Multi-angle, multi-wavelength, polarized radiances</i> | 1 | 1 | | |
| <i>Multi-wavelength imager for combined land, ocean, and cloud use</i> | 3 | 1 | | |
| <i>Microwave temperature profiler</i> | 3 | 3 | X | 3 |

| <u>Meteorology</u> | <u>DC-8</u> | <u>ER-2</u> | <u>NSF/NCAR GV</u> | <u>WB-57</u> |
|-----------------------|-------------|-------------|--------------------|--------------|
| <i>Vertical State</i> | 1 | | X | 1 |
| <i>Vertical Wind</i> | 1 | | | |
| <i>SST</i> | 1 | | | |

Candidate Deployment Sites and Nominal Range for Aircraft Operations



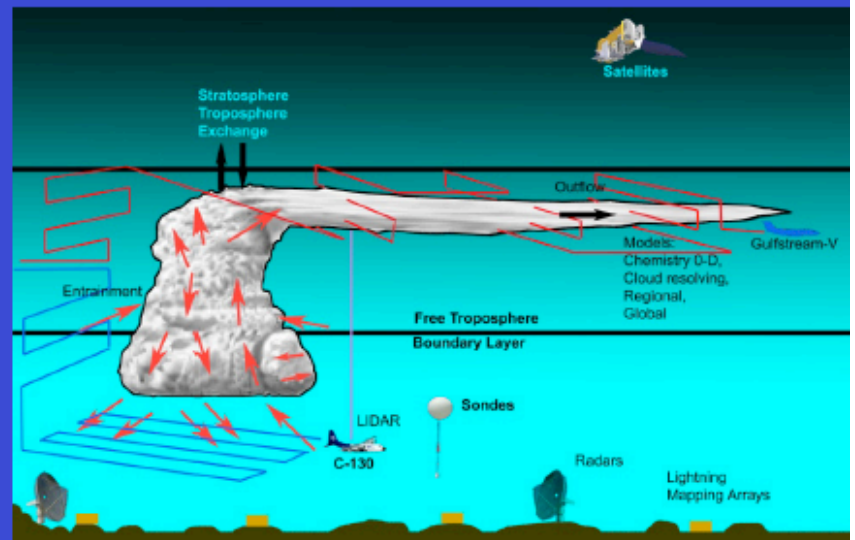
(to reach edge of ring and return requires ~6 hrs allowing ~2 hrs for loiter in an 8 hr flight)

Research Partners

7SEAS (Seven Southeast Asian Studies): a regional partnership led by NRL with a focus on interactions between pollution and local meteorology, with particular emphasis on aerosol-cloud interactions. NASA involvement already includes AERONET and SMART-COMMIT (<http://7-seas.gsfc.nasa.gov/>)

DC3 (Deep Convection, Clouds, and Chemistry): NSF-proposed experiment with a focus on impacts of deep convection on UT composition and chemistry. Goals align well with PAC³E and similarly requires multiple platforms to adequately sample influence throughout the full tropospheric column. Strong interest has been expressed in cooperation and sharing of platforms.

(<http://utls.tiimes.ucar.edu/science/dc3.html>)



Research Partners (continued)

SHADOZ (Southern Hemisphere ADditional Ozonesondes), IAGOS/MOZAIC and CARIBIC

- Data from these groups have historically provided important regional and long-term context for interpretation of more targeted field campaign observations (e.g., INTEX, TC-4, ARCTAS).
- SHADOZ anticipates the addition of Hanoi, providing a total of three sites in the study region

